UNION GÉODÉSIQUE ET GÉOPHYSIQUE INTERNATIONALE
INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS

ASSOCIATION INTERNATIONALE D'HYDROLOGIE SCIENTIFIQUE

INTERNATIONAL ASSOCIATION OF SCIENTIFIC HYDROLOGY

COLLOQUE DE HANNOVERSCH-MÜNDEN

8—14 SEPT. 1959

SYMPOSIUM OF HANNOVERSCH-MÜNDEN

TOME II — VOLUME II
LYSIMÈTRES — LYSIMETERS

PUBLIÉ AVEC L'AIDE FINANCIÈRE DE L'UNESCO

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LYSIMETERS IN THE NETHERLANDS

by G. F. MAKKINK
Technical Secretary of the Working Party for Lysimeters in the Netherlands

SUMMARY

A survey has been given on the existing lysimeter sets in the Netherlands; their aims, construction, vegetations, instrumental arrangements and research possibilities were discussed.

To make the most profitable use of the lysimeter installations and observations the Committee for Hydrological Research in the Netherlands initiated in 1949 a working party on lysimeters. Something of the way in which it works and co-ordinates the research has been dealt with.

The general rectilinear regression of yearly rain quantity on yearly drainage quantity is mentioned.

Finally a few examples have been given of the transfer of the results of lysimeters to regions with natural and agricultural vegetations elsewhere in the country and of the check on these calculations.

A bibliography on Dutch lysimeter research concludes the paper.

RESUMO

Superrigardo estas donita pri la ekzistantaj lizimetraroj en Nederlando; iliaj celo, konstruo, vegetacio, instrumentaj arangoj kaj esplor-ebloj estas traktitaj.

Por plej efike uzi la lizimetrojn kaj iliajn observojn la Komitato por hidrologia esploro en Nederlando starigis en 1949 Laborgrupon pri lizimetroj. Kiel gi funkcias kaj kunordigas la esploradon estas kommunikita.

La generala rektlina rigreso inter jara drenkvanto kaj pluvkvanto estas menciita.

Fine kelkaj ekzemploj estas donitaj pri la aplikado de la rezultoj pri lizimetroj en regionoj kun naturaj kaj agrikulturaj vegetacioj aliloke en la lando, kie kontrolo lau aliaj esplormetodoj okazis.

Bibliografio pri Nederlanda lizimetro-esplorado finas la artikolon.

LYSIMETERS

Lysimeter observation in the Netherlands has started in 1876 at Oude Wetering (near Leiden), but from the period 1876-1901 no data have been published.

On this moment there are six lysimeter sets in the Netherlands, whereas formerly there were four sets more. In total they comprise now 57 individual lysimeters, which are filled with 7 different soil types.

A set of 8 percolation gauges at Groningen (Institute for Soil Fertility) has been constructed to study the leaching, maturing and aging of the marine sandy loam of newly reclaimed polders in the North of the country. The aim is chemical research in the first place, hydrological research in the second place.

One set of 5 has been erected by the Water Board of Amsterdam to observe the amount of drain water in the dune region. In this area where the drinking water is collected, it is necessary to gain an insight into the relationship between drainage and rainfall to avoid exhaustion of the ground-water reservoir.

The second set in the dune region, 4 large lysimeters of 625 spuare meter owned by the Provincial Water Works of North Holland, has been built to study the effect of afforestation on the amount of water percolating to the natural drinking water reservoir. One is covered with pine wood, another with deciduous wood, a third with natural dune vegetation, and the last is kept bare.

At Oude Wetering the Polder Board of Rijnland owns 4 lysimeters, serving to give directions on the management of a correct level and quality of the water in the canals and ditches of the district. Two are filled with dune sand and cropped with flowerbulbs, the economically most important crop of the district and sensitive to water shortage. The other two have a peat soil with permanent grassland, representing the general vegetation of the district.

There are 4 lysimeters in a small polder near Groningen, where plots of 25 x 25 m^2 are surrounded by wooden walls of bulk heads to avoid horizontal movement of water. The waterlevel inside is accurately maintained at -80 cm. For those plots as well as for the polder as a whole a water balance sheet is set up, for the plots every month and for the polder four times a year. Gravimetric moisture determinations, made periodically, enable to calculate the actual evaporation. This work is done with no other aim than research work, especially to study the validity and usefulness of the theory of turbulent water vapour exchange. An installation to record the vertical gradients of wind velocity and vapour pressure deficit is present. This research is carried out under responsibility of the Government Hydrological Service, in which other Government services take part, such as the Royal Netherlands Meteorological Institute, the Institute for Soil Fertility and the Institute for Land and Water Management Research.

Finally the Institute for Land and Water Management Research has a set of 32 lysimeters with an area of 1 square meter each. They contain a sandy soil, a peat soil and a clay soil covered with permanent grassland. They are monoliths and at least as far as concerns the sandy and clay soil, they have the original turf on top of them. This is the only installation with weighing possibilities. The object was to study the relationships between evaporation and water management on the one hand, and between water management and grass production on the other hand. They now serve mainly to check theories on water movement in the soil and to observe evapotranspiration.

A detailed description of the lysimeters I shall not give. This has already been done by Wind (1958) in a paper in which also designs can be found. A short survey is given in table 1. I shall only mention a few details, which are important for the investigation and its results.

1. Most of the lysimeters have a water table, which can be kept constant or, as at the lysimeters at Wageningen, can be regulated according to the aim of the investigation. In Castricum and in Groningen a rising of the water table above the accepted level can be prevented, a falling, however, cannot.
2. Precautions were taken with all lysimeter sets that the vegetation be homogeneous with the surroundings. At Castricum, Oude Wetering and Groningen a borderzone of the same vegetation was created. In Leiduin, Wageningen and the Rottegatspolder, the vegetation was the same as that of the surrounding vegetation.
3. According to the weighing in Wageningen there is a gap of 16 cm between the grass on and that around the lysimeters. Therefore they may receive more radiation and have a higher evapotranspiration accordingly.

TABLE 1

A survey of the lysimeters

locality	number	area m²	depth m	water table m	soil		vegetation		observ. since
Castricum	4	625	2,50	—2,25 or>	dune sand	F	bare, natural dune veg., pine wood, deciduous wood	Z (3)	1942
Groningen	8	0,89	1,40	—1,00 or>(4)	marine sandy loam	F	any agric. crop or bare (8)	Z-B	1919
Leiduin	5	1,00(3) 1,9 (2)	1,25(3) 5,00(2)	—~ (3) —4,50(2)	dune sand	F	poor grass		1929 (3) 1944 (2)
Oude Wetering	4	1,00	1,03	—~ (2) —0,63(2)	humous dune sand(2) peat soil(2)	F	bulb flowers grass	Z-B	1942
Wageningen	32	1,00	1,00(20) 1,50(12)	different: constant or alterated	sand(8) clay(12) peat(12)	MW	permanent grassland	G	1952
Rottegats-polder	4	625	0,93	—0,80	clay	PD	limited crop rotation		1950
	57								

D = periodical moisture determinations
F = filled in
M = monolith
P = part of field, tiles dug in
W = weighable

B = buildings in the neighbourhood
G = gap of 16 cm between grass on and that around lysimeters
Z = on a bordering zone the same vegetation as on the lysimeter

4. In Oude Wetering and in Groningen there are houses and buildings rather close to the lysimeter. Therefore the local climate is not quite the same as in the open country. The yearly evaporation of the lysimeters at Groningen is on the average 85 pct of that of the drain-lysimeters in the Rottegatspolder at a distance of 10 km.
5. Near the lysimeters at Castricum and in the Rottegatspolder there is an extensive meteorological equipment, a modest one near the lysimeters at Wageningen, whereas the others have only a few accessory instruments, such as a rain gauge, a thermometer, etc. Five installations have evaporation pans.

Working Party

In June 1949 a Working Party on lysimeter research was installed by the Committee for Hydrological Research, one of the 45 Committees, Institutions, Services and Laboratories affiliated by the Central National Council for applied Scientific Research in the Netherlands.

In this Working Party each institution, owning lysimeters is represented, whereas also the Royal Netherlands Meteorological Institute and the Government Hydrological Service take part in it. Moreover three specialists on evaporation, on water management of polders, and on groundwater levels are members.

Since 1953 an investigator has been charged with a co-ordinated study of all lysimeter observations, placed at his disposal by the owning institutions. He was in the service of the Committee for Hydrological Research but responsible to the Working Party, and therefore he discussed his work regularly with its technical secretary. The quaterly reports of the investigator are discussed in regular meetings of the Working Party.

It is considered the final aim of lysimeter research to gain an insight into the water balance of any natural soil profile as a function of climate, vegetation and movement of the groundwater. This aim widely surpasses the limited scope of the lysimeter observation of the separate institutions who own them. This has consequences for the way of elaboration of the data. It also requires co-ordination of the observation itself. This work has led to the desirability of additional information about the vertical distribution of moisture in the lysimeter throughout the year. In this way water balance equations for shorter periods than a year can be solved. Therefore in the lysimeters at Wageningen, Castricum and Groningen electric resistance units and thermistors have been installed, the readings of which are made by the personnel of the respective institutions. Also data on the evaporation of free water are computed on the base of application of the Penman-formula and the variations of the water table in the areas the lysimeters represent, are observed.

As the investigator in charge Dr. Wind died last year, the research worker of one of the owning institutions is now in charge of the whole co-ordinative work, but he can be only partly responsible to the Working Party.

The work of Dr. Wind has given considerable results; I will quote a few of them to show that the data of lysimeters may have a much wider field of application than is generally believed.

The lysimeter formula

For lysimeters which cannot be weighed, a water balance sheet can be set up only for periods in which the moisture content of the soil is the

same at the beginning and at the end. This is the case for the hydrologic year from April 1st till March 31st. Plotting drainwater quantity (D) against rainfall (R), a straight regression line is obtained as figures 1 and 2 demonstrate. Figure 3 demonstrates a great scattering.

This regression can be represented by the equation

$$D = a R - b$$

in which a and b are constants.

Although the standard deviation of a and b is generally high, the application elsewhere leads to results, which are promising. Three examples, in which a check was made by other investigations, were studied.

Transfer of lysimeter results

1. For the NW part of the Veluwe (the sandy soil region in the centre of the country) the Service of the Zuiderzee Works carried out hydrological investigations on the base of Darcy's formula in 1948, 1949 and 1950. From these the average yearly drainage could be calculated as 320 mm.

The vegetation of this region consisted of

pine wood	44 pct
deciduous wood	12 „
heather and sand	27 „
arable land	9 „
grassland	7 „

For the consecutive vegetations the drainage formulae of various lysimeters were applied, namely of Castricum (pine wood on dune sand), Castricum (deciduous wood on dune sand), Castricum (dune vegetation and bare dune sand, averaged), Groningen (arable crops on sandy loam), Wageningen (grass on sandy soil).

The result was 321 mm, a striking conformity.

2. For the Rottegatspolder (87 ha) the complete water balance sheet has been studied, the variations in the soil moisture included. From this the average yearly evapotranspiration for the period 1949 till 1954 incl. was found: 506 mm.

The vegetation during this period consisted on an average of:

arable land	67 pct
grassland	21 „
gardens and road shoulders	2 „
roads, farm yards	1,5 „
ditches, open water	8,5 „

The drainage formulae applied, were:
that of Groningen (arable crops on sandy loam) for arable land and that of Wageningen (grass on clay soil) for grassland, gardens and road shoulders. For roads and farm yards D is supposed to be equal to R, for open water D is taken equal to R-E_0. The average apparent evaporation (R-D) becomes 502 mm then, whereas the average result from the water balance was 506 mm.

3. For three catchment areas of small streams in the Eastern and Southern part of the country the evapotranspiration was calculated by Ir. Stolp for the period 1948-1953 incl. In all three the vegetation consisted of about 57 pct arable land and about 43 pct grassland. The drainage formulae applied were those of Groningen (arable crops on sandy loam) and of

Wageningen (grass on sandy soil). The average apparent evaporation (R-D) found with the formulae and that calculated by Ir. Stolp, were:

	formula	Ir. Stolp
a	507	507
b	513	491
c	518	488

The conformity is good to satisfactory, the greatest deviation being only 6 pct.

For further details I may point to three publications, made by Dr. Wind during his service of the Working Party, on lysimeter research in the Netherlands, mentioned in the following bibliography of Dutch investigations by means of lysimeters.

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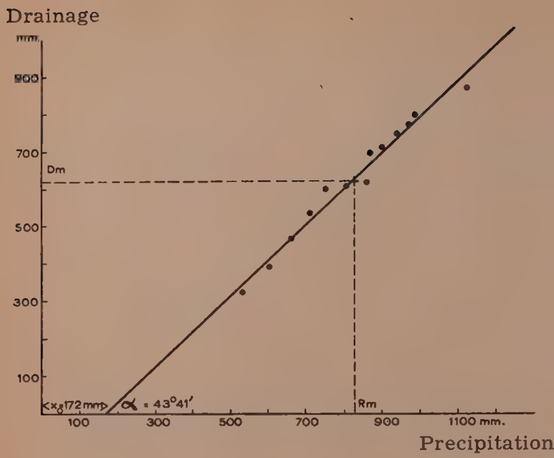

Fig. 1 Yearly values of draina
quantity plotted against ra
quantity, concerning the lys
meter with bare dune sand
Castricum (1942—1953).
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metitaj kontrau valoroj p
pluvkvanto, koncernante la
zimetron kun nuda sablo
Castricum (1942—1953).

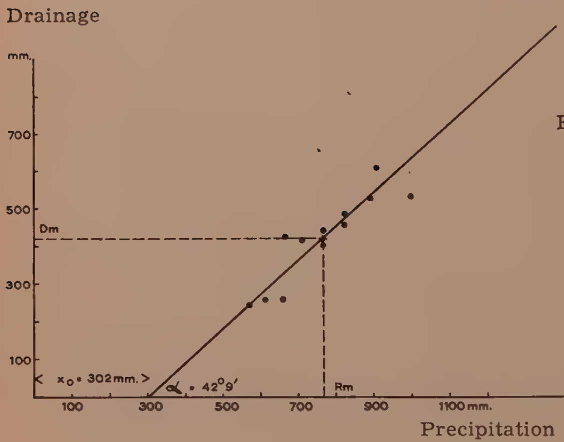

Fig. 2 Similar figure as fig. 1 conce
ning the lysimeter with gra
on peat soil and a consta
water table at Oude Weteri
(1943—1954).
Simila figuro kiel fig. 1 ko
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stanta akvonivelo ce Oude W
tering (1943—1954).

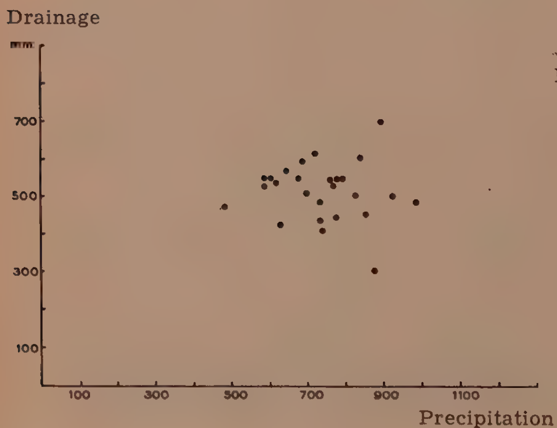

Fig. 3 Similar figure as figure 1, co
cerning the lysimeters wi
sandy loam at Groningen. E
dot represents the average
8 lysimeters with the sa
crop. Only years with ara
crops (1919—1933, 1939, 19
1946—1954).
Simila figuro kiel fig. 1, ko
cernanta la lizimetrojn k
sabla argilo en Groningen.
punkto reprezentas la me
mon de 8 lizimetroj kun
sama kreskajo. Nur jaroj k
agrikulturaj plantoj (1919—19
1939, 1940, 1946—1954).

LIMITATIONS AND PERSPECTIVES OF LYSIMETER RESEARCH

by G. F. MAKKINK
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SUMMARY

Most lysimeters have limitations. Imperfections may cause that the hydrological phenomena observed do not fully represent what occurs in nature. Some are: 1) discontinuity of the vegetation on the lysimeter and surrounding it, or a lack of vegetation around it; 2) heterogenity of the soil, possibly due to the small size of the lysimeter; 3) too great a difference between the waterregime in the lysimeter and in the surrounding area; 4) the being filled in, versus monolith.

The lack of weighing possibility is a limitation reducing the figures on evaporation to one a year. This shortcoming might be compensated for by installing electrical resistance units and thermistors for determination of water content in the lysimeters at any moment. Increase of the number of observation periods also results from the use of the natural drainage period, which is at least also applicable for grass on light soils.

The drainage-rainfall-formula for hydrological years, applied for concerning periods elsewhere, seems to be promising. An analytical, schematic approach on the base of evaporation formula, water book-keeping and soil and crop parameters, the latter connected with crop height, enables to compute actual evapotranspiration for periods of a month or shorter. This method has given satisfactory results. The lysimeters which satisfy certain requirements, can provide the necessary constants, thus enabling extrapolation of results to application elsewhere.

RESUMO

Multaj lizimetroj havas limigojn. Malperfektajoj kauzas ke la observataj hidrologiaj fenomenoj ne tute reprezentas tiujn kiuj okazas en la naturo. Kelkaj estas: 1) interrompiteco de la vegetacio sur kaj cirkau la lizimetro au manko de cirkauanta vegetacio; 2) malhomogeneco de la grundo, eble sekve de malgrandaj mezuroj de la lizimetro; 3) tro granda diferenco inter la akvoregimo en la lizimetro kaj tiu de la ekstera tereno; 4) la disfositeco de la grundo.

La manko de peseblo estas limigo kiu reduktas la nombron de ciferoj pri elvaporigo al unu jare.

La lasta manko estas kompensebla kiam oni instalas elektrajn rezistoelementojn kaj termistrojn por determini la akvoenhavon en la lizimetroj je ciu ajn momento. Plinombrigon de la observperiodoj oni povas atingi ankau per aplikado de la metodo de naturaj drenperiodoj, kiu almenau estas aplikebla ankau ce greso sur sablaj grundoj.

Aplikado de la drenakvo-pluvakvo-formulo pri hidrologiaj jaroj por aliaj lokoj estas promesa. Analiza, skema metodo surbaze de la elvaporig-formulo, akvolibrotenado kaj grund- kaj plantar-parametroj (la lastaj rilatigitaj al la alteco de la plantaro), ebligas kalkuli la efektivan elvaporigon en periodoj de unu monato au pli mallongaj. Tiu ci metodo donis kontentigajn rezultojn. La lizimetroj kiuj kontentigas certajn postulojn, povas liveri la necesajn parametrojn, tiel ebligante ekstrapoladon de rezultoj al aliaj lokoj.

1. INTRODUCTION

Most lysimeters have limitations. These are of to two kinds. The first is a number of imperfections which cause the hydrological and even agricultural

phenomena to be not fully representative of what occurs in the field, for example the lack of a surrounding crop, absence of a watertable, too small a size, etc. Some of them can be avoided.

The second kind of limitation concerns the absence of weighing possibilities, which implies that generally only one correct yearly figure on evaporation can be obtained. This concerns the hydrological year, beginning and ending at a time, when the soil may be supposed to have the same moisture content. In the Netherlands we take the cycle March 1st-February 28th or April 1st-March 31st.

2. Limitations

Discontinuity of vegetation

If the surface of the lysimeters—cropped or bare—is not continuous with the surrounding area, evaporation is influenced by border effects, which will cause an error which can be considerable with small lysimeters. Since radiation is considered to be the most important factor controlling evaporation, directly or indirectly, a partly or totally lacking of a vegetation will lead to overestimated values.

For the lysimeters at Wageningen I calculated the extra radiation the grass cover received due to the circular flange and pitwall (together 16 cm wide) (Makkink 1957 a). This border caused a gaplike interruption in the vegetation of the lysimeters and the surrounding grass. The grass was supposed to stand upright.

period 1953	grass length, cm	extra radiation %
24/4 — 2/5	8.5	14
22/5 —30/5	13	17
19/6 —27/6	8	10
17/7 —25/7	11	16
14/8 —22/8	8	14
11/9 —19/9	7	16
8/10—16/10	6	18

If the grass would hang over the gap equally on both sides, the lysimeter would receive 30.5 % extra radiation. The extra radiation can lead to corresponding extra evapotranspiration.

Heterogenity of the soil

Another limitation inherent to the small size of most lysimeters is the heterogenity of the soil. Three of the lysimeters at Wageningen (sand, clay and peat) have been provided with a concentric steel rim inside the bottom piece, placed in such a way that the area inside the rim was equal to the area outside it. Observation showed that drainage as well as infiltration from below were very different in the central and peripheral halves. Some-

soil type	number	K-value m/24 h					
		min.		average (1)		max.	extreme values
sand	8	0.06	—	0.16	—	0.35	—
peat	12	0.26	—	0.52	—	0.74	(1.52, 4.10)
clay	12	< 0.01	—	0.38	—	1.14	(2.41, 2.70, 2.72, 3.10)

times the central part had a higher quantity of drainage than the peripheral part, but in another period the reverse occured. No regularity could be detected. Perhaps the distribution of cracks, rootholes and wormholes determined the phenomenon.

Heterogenity of the soil was also found between the lysimeters filled with monoliths of the same parcel. A determination of the permeability (K-value) of the soil in the 32 lysimeters at Wageningen in wintertime showed very divergent values for each soil type, notwithstanding the fact that the monoliths were taken a few meters from each other on the same field.

Deviating waterregime

Another limitation can be due to the fact that the waterregime of a lysimeter is not the same as that of the surroundings. Then evapotranspiration will also differ. To obtain representative values for the actual evapotranspiration of a certain area, the availability of water within the lysimeter should be about the same as that without.

Many lysimeters have no water table and have a modest depth. Since the drainwater flows out when the critical hydrostatic pressure surpasses the surface tension of the water in the soil pores, the drainage in an interrupted soil column will occur at a higher moisture content than in a column in situ, where a negative suction is present at the concerning depth (Colman, 1946). Crop yield and consumption of minerals can be considerably increased in comparison with lysimeters in which the correct soil suction is imitated (Wallihan 1940). In lysimeters with a naturally regulated water table this problem does not exist. Lysimeters with free drainage should be so deep that the roots do not reach the zone with abnormal water conditions.

If a moist water regime prevails in a lysimeter and a dry one in the surroundings, there is not only a difference in evapotranspiration due to the different water conditions in the soil, but the evapotranspiration from the lysimeter is also increased according to the advective heat from the surrounding dry area (Penman 1956). If in such a situation the potential evapotranspiration of the lysimeter is calculated with Penman's formula, the result will be below the observed value, because the formula does not account for advective heat (Makkink 1957 b).

Disturbed soil

A much discussed limitation is caused by the filling in of the soil into the lysimeter. From a comparison of the structure of the dune sand in the

(1) without extreme values.

lysimeters at Castricum and of the not disturbed soil outside it, there was a smaller variety of pore space categories in the disturbed soil than in the undisturbed soil (Peerlkamp 1948). After 10 years the difference seemed to have become smaller (Wind, being printed).

Since the wider pores are responsible for faster percolation and for better aeration, a difference in structure will influence the conditions of crops and soil life and, therefore, may cause a difference in evaporation. No observations are made on the magnitude of such a difference.

3. Amplification and better utilization

To increase the number of data on evaporation for lysimeters which cannot be weighed there are two ways.

Moisture determinations

Measurements of soil moisture in the successive layers of the soil in the lysimeter can regularly be made by installing electric resistance units and thermistors or by making use of the newly developed method with gamma rays.

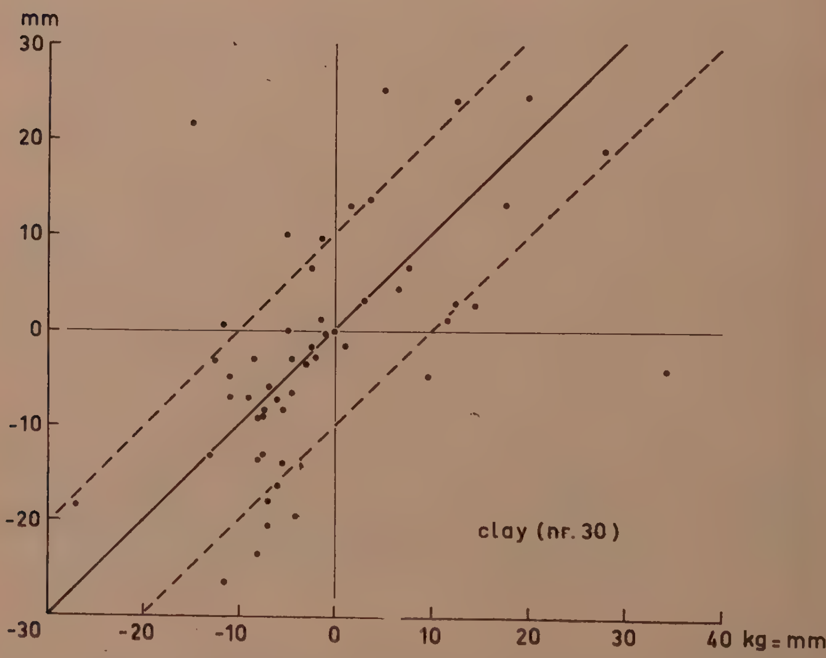

Fig. 1 Changes of water content electrically measured (ordinate) plotted against changes in weight (abscissa) with lysimeter nr. 30 (clay) at Wageningen in 1956. Measurements mostly twice a week.

Sangigoj de la akvoenhavo, elektre determinita (ordinato) metita kontrau sangigoj de la pezo (absciso) ce lizimetro n-ro 30 (argilo) apud Wageningen en 1956. Determinoj kutime du fojojn en semajno.

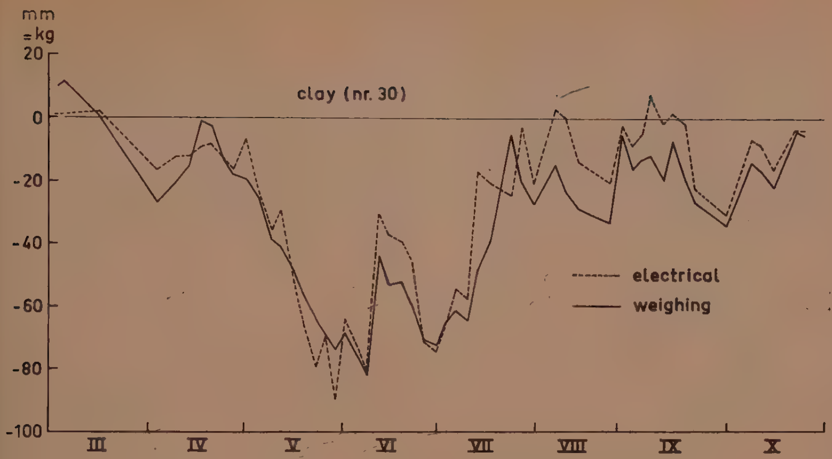

Fig. 2 Differences of water content (electrically measured) and of weight since January 17th throughout 1956 with lysimeter nr. 30 (clay) at Wageningen.
Diferencoj de la akvoenhavo (elektre determinita) kaj de la pezo depost la 17-a de januaro 1956 ce lizimetro n-ro 30 (argilo) apud Wageningen.

In a number of lysimeters at Wageningen one set of nylon resistance units and thermistors were installed throughout the profile. Measurements of the electric resistance twice a week, reversed to changes in moisture content, made a comparison possible with the changes of weight of the lysimeters in the corresponding periods. The data showed a considerable scattering, when plotted one against the other (Fig. 1). This can be due to the inaccuracy of the electric method, to hysteresis or to inhomogeneousness of the soil block. The time curve of a lysimeter with a clay soil shows that after the summer dryness there is a systematic discrepancy, which grows smaller towards winter (Fig. 2). It seems that with rewetting of the clay the electrical resistance suggests a higher moisture content than there is really present. This may be due to a phenomenon like hysteresis. For the time being this method cannot replace weighing.

Natural drainage periods

Penman and Schofield (1941) introduced for the fallow soil in the lysimeters at Rothamsted the "natural drainage period", being the period between two successive moments when drainage stops. For this period E = R—D if the rainfall (R) is taken according to the quantities which made drainage (D) cease (not at the same moments the latter occurs). Those periods are determined by nature, not by the investigator.

For cropped lysimeters with a rather extended root zone, it is difficult to state which quantities of rain were the last that maintained drainage. For a number of lysimeters with a constant water table at —50 cm or —70 cm (all with grass) it was investigated whether E, calculated from the waterbalance sheet of the natural drainage periods was equal to E based on weighings.

Or in other words whether there was no change of weight in natural drainage periods.

For a sandy soil (Fig. 3) the scattering is rather small, for peat soil, however, greater and for clay soil (Fig. 4) considerable. The length of the periods with sand was 9—33 days (average 18), with peat soil 15—55 days (average 32), and with clay soil 15—110 days (average 34). The natural drainage period method, therefore, merits further application for light soils with a constant water table and perhaps also with a naturally changing water table and with free drainage. Those periods must not be too short.

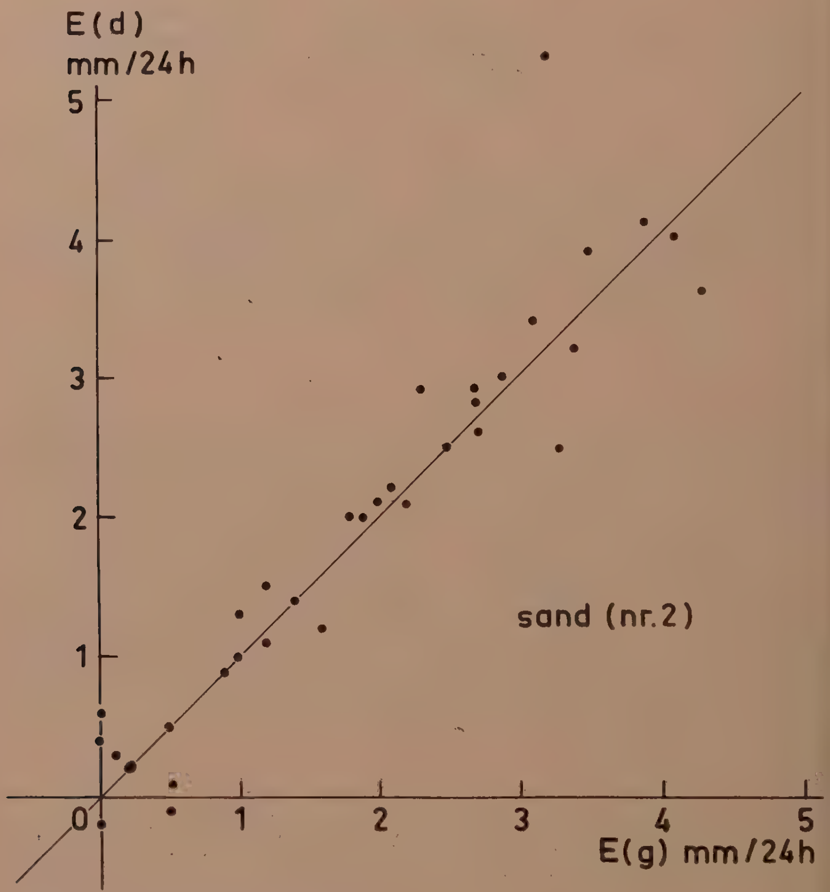

Fig. 3 Evapotranspiration per day of grass on lysimeter nr. 2 (sand) with a constant water table at -50 cm at Wageningen in 1952 and 1953. Values according to the waterbalance sheet of natural drainage periods (ordinate E (d)) plotted against values according to weighings (abscissa E (g)).

Evapotranspiro po tago el greso sur lizimetro n-ro 2 kun konstanta akvonivelo je -50 cm apud Wageningen en 1952 kaj 1953. Valoroj el la akvobilanco pri naturaj drenperiodoj (ordinato E (d)) metitaj kontrau valoroj el pezadoj (absciso E (g)).

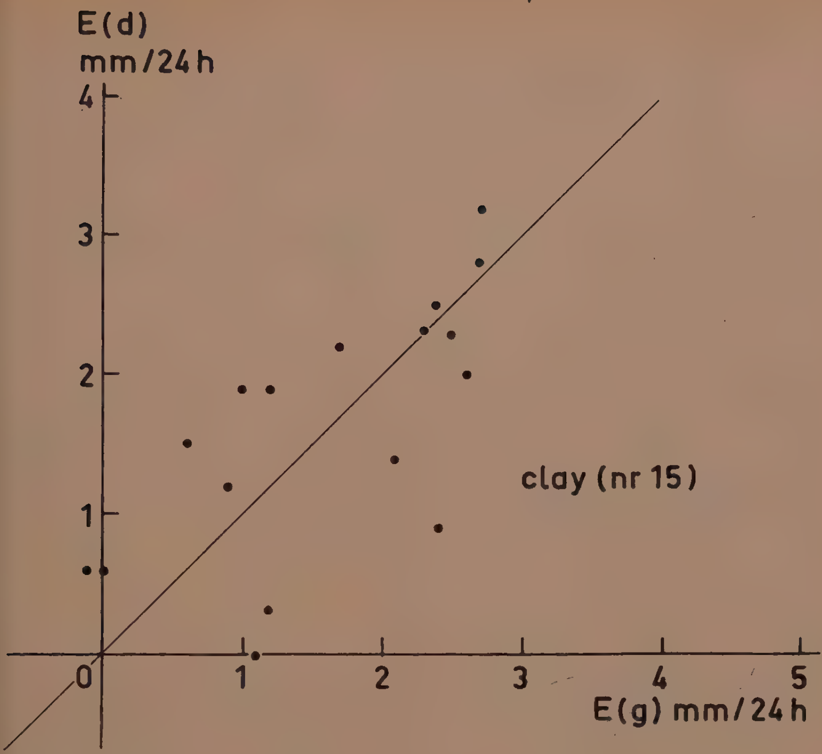

Fig. 4 As figure 3 for lysimeter nr. 15 (clay) with a constant water table at -70 cm; Wageningen 1952 and 1953.
Kiel figuro 3 pri lizimetro n-ro 15 (argilo) kun konstanta akvonivelo je -70 cm; Wageningen 1952 kaj 1953.

4. Perspectives

Emperical extrapolation to field conditions

In the other paper given in this symposium I quoted Winds application of the lysimeter-formula of hydrologic years to areas with the same or a similar vegetation.

This procedure has led to promising results and therefore deserves wider application.

Analytical extrapolation to field conditions

Another procedure of extrapolation can be developed on an analytical basis. It enables calculation of actual evapotranspiration in periods of a month or shorter. With this method the year cyclus is divided into short periods (pentades or days, according to expected errors). For each period the evapotranspiration is either potential (E_P) or sub-potential (E_R), depending on the amount of available water (A). In a formula:

$$E = E_p \,\Big|\, (E_p \leqq A) \qquad (1a)$$

$$E = E_R \,\Big|\, (E_p > A) \qquad (1b)$$

For a longer period, for example a month, the summarized formula is then:

$$\Sigma E = \Sigma E_p \,\Big|\, (E_p \leqq A) + \Sigma E_R \,\Big|\, (E_p > A) \qquad (2)$$

A fallow soil and a dense crop may be considered as special cases of a soil that looses its water to the atmosphere due to both evaporation and transpiration. In the case of potential waterloss, therefore

$$E_p = E_Z + E_X \qquad (3)$$

if the index Z concerns potential evaporation from bare soil and X potential transpiration from any kind of crop.

For a short and dense grass cover, optimally provided with water, the potential waterloss (E_p, index minuscule) can easily be calculated according to Penman (1956) or to Makkink (1957b). To relate E_Z and E_X to E_p a factor g_X resp. g_Z is added, the value of which depends on the degree of bareness of the soil resp. the height or the density of the crop. Thus:

$$E_Z = g_Z E_p \qquad (4a)$$

$$E_X = g_X E_p \qquad (4b)$$

and for a partly covered soil, therefore,

$$E_p = (g_Z + g_X) E_p \qquad (5)$$

When the evapotranspiration is sub-potential the available water limits water loss to the atmosphere. In this case the water loss can comprise the rain (R), the actual amount of water in the root zone or in the upper layer from which evaporation occurs (w_r) and the amount of water which is reached by root growth during the short period ($\triangle w_{vX}$, v indicates that the soil is at maximum field tension). w_r cannot exceed w_{vZ} for bare soil or w_{vX} of cropped soil.

$$E_R = R + w_r + \triangle w_{vX} \qquad (6)$$

From (2), (5) and (6) we obtain the general formula:

$$\Sigma E + \Sigma (g_Z + g_X) E_p \,\Big|\, (E_p \leqq A) + \Sigma (R + w_r + \triangle w_{vX}) \,\Big|\, E_p > A) \qquad (7)$$

It is possible to distinguish five periods:

1) a period between ploughing and the appearance of the crop (period with fallow soil)
2) a period between the appearance of the crop and the moment the crop is equivalent to a dense, short grass cover ($g_X = 1$); period with more or less covered soil
3) a period when the soil is "completely covered" with a green crop ($g_X > 1$)
4) a period between ripening and harvest when the crop is yellowing and drying)
5) a period between harvest and ploughing; soil fallow with remainings of the crop on and in the soil.

In period 1 $g_X = O$ and $\triangle w_{vX} = O$ in the equation (7). Since a wet soil evaporates according to E_o,

$$g_Z = E_o / E_p \qquad (8)$$

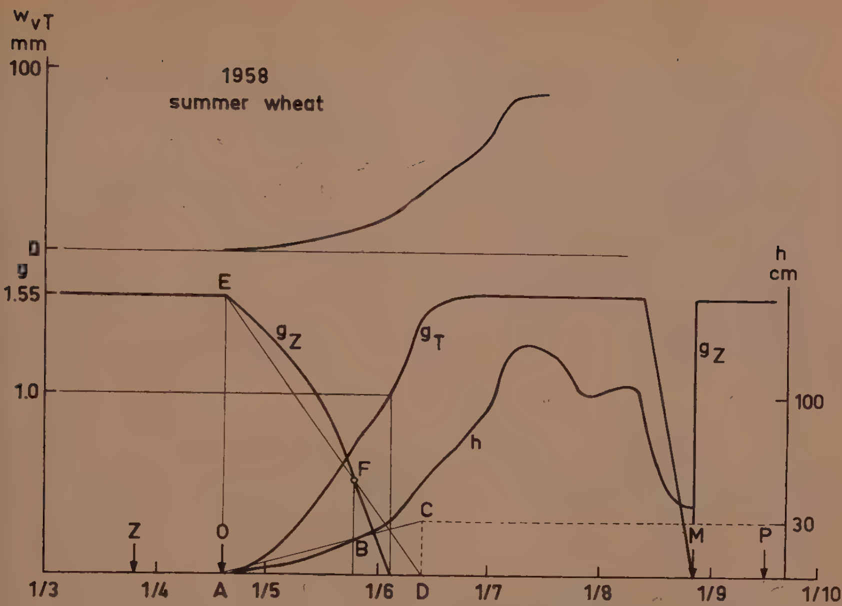

Fig. 5 Above: curve of w_v for wheat (T) against time. Below: curves of g for wheat (T) and fallow soil (Z) and of height (h) of wheat against time. Arrows at the bottom point to dates of sowing (Z), appearance (O), mowing (M) and ploughing (P). Lysimeters Rottegatspolder in 1958.

Supre: kurbo pri w_v de tritiko (T) kontrau la tempo. Malsupre: kurboj pri g de tritiko (T) kaj de nuda tero (Z) kaj de la alto (h) de la tritiko kontrau la tempo. La sagoj ce la bazo montras al datoj de semado (Z), de elterigo (O), de falcado (M) kaj de plugado (P). Lizimetroj en Rottegatspolder en 1958.

E_o representing the evaporation from a free water surface. In period 2 equation (7) works fully. In periods 3 and 4 in the equation (7) g_{pZ} is O. In period 5 g_X is O, but w_{vX} has a value between w_{vZ} (of bare soil) and w_{vX} of the crop at the moment of harvest, because the roots are still present and are able to transport water from deeper layers to the upper evaporation layer.

There have been made a few assumptions in order to run a water book-keeping:

1) no rain water percolates through cracks and holes out of reach;
2) all water till pF 4.2 evaporates with the same ease;
3) w_{vZ} is provisionally considered to be a constant soil factor;
4) w_{vX} is supposed to be proportional to the height of the crop at every moment;
5) g_X is increasing with height of the crop but approaches a limit;
6) g_X decreases rectilinear with time during ripening;
7) when $g_X = 1$, g_Z is considered to be O;
8) g_Z gradually decreases with increase of g_X;
9) capillary rise is not taken into consideration because the water table can be supposed to be at a considerable depth.

There are a number of factors which change with time w_r, w_{vX}, g_X and g_Z.

w_r must be found in continually bookkeeping of the water content of the soil, starting at the end of the winter. For the relation of w_{vX}, g_X and g_Z with time, curves must be drawn (Fig. 5). In order to obtain those the assumption was made, that g_X and w_{vX} depend on the height of the crop. This magnitude, being simple, can easily and regularly be measured. In first approximation w_{vX} relates rectilinearly with height, g_X curvilinearly (Fig. 6). Therefore we need only one determination of evapotranspiration by means of a conventional method (V) to obtain w_{vX}; for g_X we need at least two such determinations.

w_{vX} can be determined with equation (6) if we select a period with a limited amount of available water since the beginning of growth. Then $\Sigma E_R = V = \Sigma(R + w_r + \Delta w_{vX})$, in which $w_r + \Delta w_{vX} = w_{vX}$, and this can be calculated. g_X can be determined with equation (4b):

$$\Sigma E_p = V = \Sigma g_X E_p$$

For this two periods without soil evaporation and an abundant amount of water will suffice. The course of g_Z with time can now graphically be found, recognizing that at the moment of appearance of the crop

$$g_Z = E_o / E_p \tag{8}$$

and that at the moment $g_X = 1$ (see time curve of g_X) the vegetation is equivalent to a dense short grass cover, so that g_Z may be considered to be O.

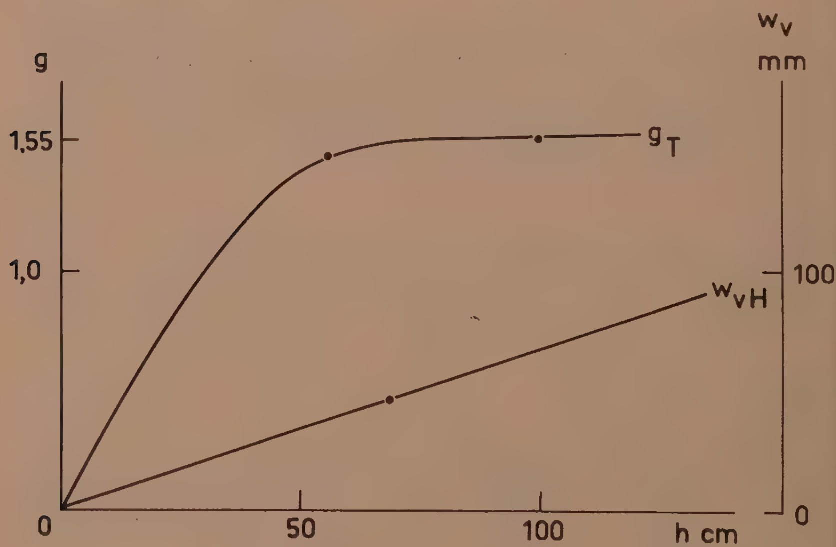

Fig. 6 Curves of g against height (h) for wheat (T) and of w_v against height (h) for oats (H). The dots represent observed values. Lysimeters Rottegatspolder.

Kurboj de g kontrau la alto (h) ce tritiko (T) kaj de w_v kontrau la alto (h) ce aveno (H). La punktoj prezentas observitajn valorojn. Lizimetroj Rottegatspolder.

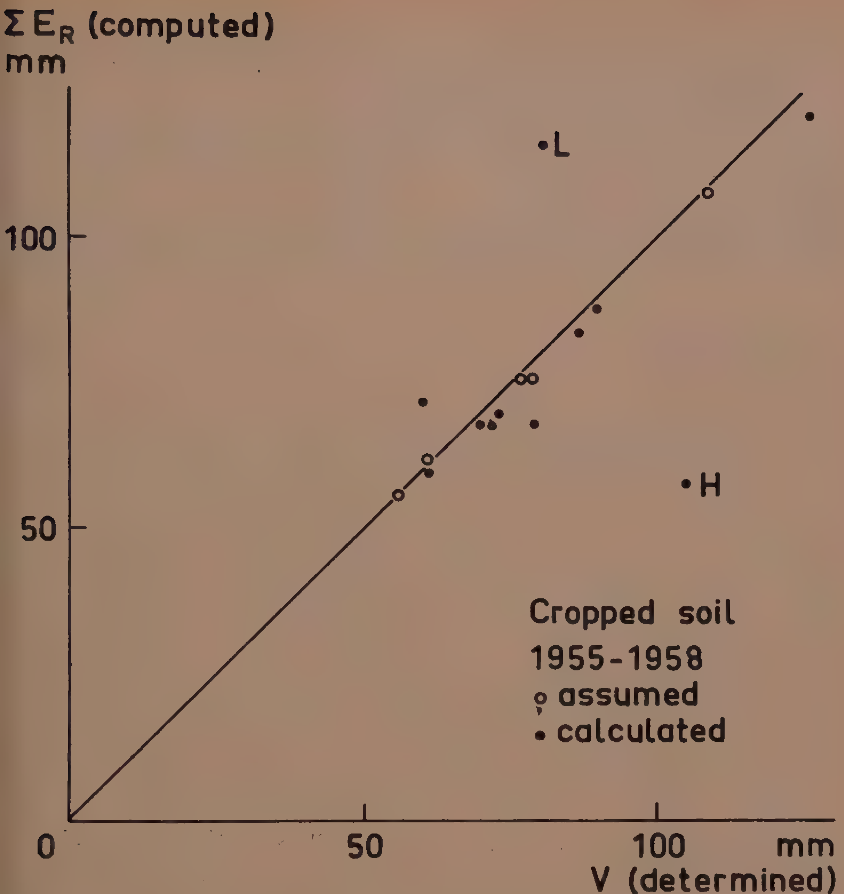

Fig. 7 Actual evapotranspiration of cropped soil in monthly periods en 1955-1958 incl.; lysimeters Rottegatspolder. Computed values (ΣE_R) plotted against observed values (V). Assumed values according to observation: o. L.: lodging of wheat; H: oats, when no capillary rise of water or root growth after growth stop of top is supposed.

Efektiva evapotranspiro el plantita tero en monataj periodoj en 1955-1958 inkl.; lizimetroj Rottegatspolder. Kalkulitaj valoroj (ΣE_R) metitaj kontrau observitaj valoroj (V). Valoroj adaptitaj al la observoj: o. L: ekkuso de tritiko; H: aveno, se oni ne supozas kapilaran akvolevigon au plukreskon de la radikaro post ceso de la kresko de la tigo.

Finally w_{vZ} can be determined with (6) from one dry period with bare soil after ploughing. This highly schematic model was checked for the drainage lysimeters in the Rottegatspolder, where the actual evapotranspiration V was already determined for periods of about a month.

For wheat the relationship of w_{vX} with height of oats was used, for oats the relationship of g_X with height of wheat was used. E_p was calculated according to Makkink (1957b).

For the cropped periods data of 4 years with wheat or oats were at the disposal (Fig. 7), for the fallow periods date of 7 years (Fig. 8).

Of the 16 periods with a cropped soil (Fig. 7) 5 were used to determine the necessary parameters. Of the other 11 dots two deviate largely. The higher one concerns a wheat crop lodging after heavy rains; the lower one concernes oats in a very dry period. In this latter case capillary transport within the soil block or root growth during ripening can explain the deviation.

The fallow periods show greater scattering (Fig. 6). This is partly due to snow and ice (crosses) influencing the checking values more than the

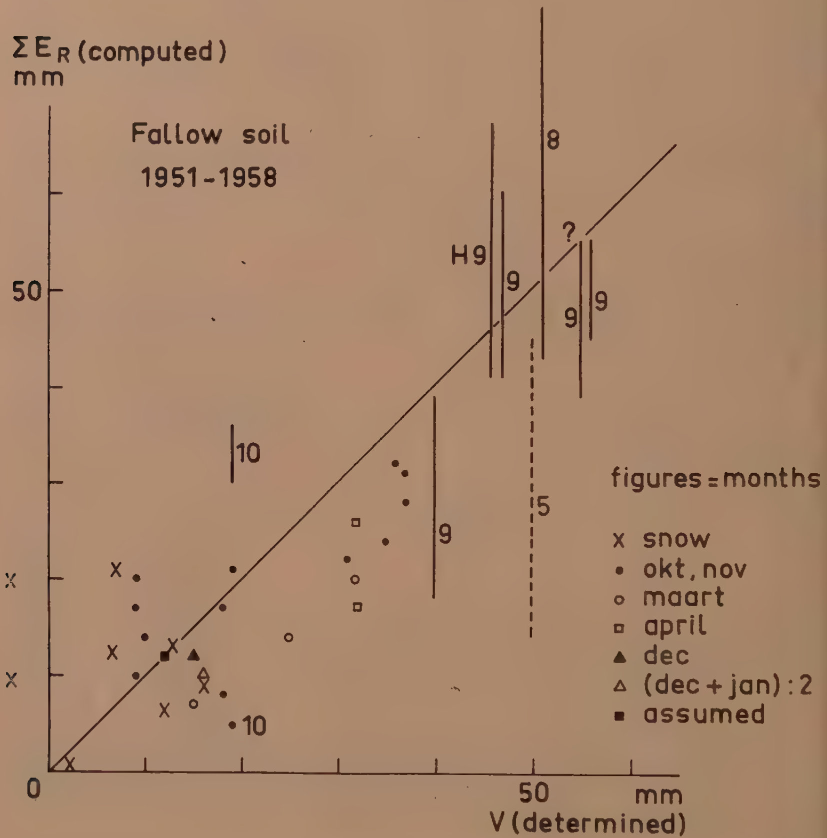

Fig. 8 Actual evaporation of fallow soil in monthly periods in 1951-1958 incl.; lysimeters Rottegatspolder. Computed values (ΣE_R) plotted against observed values (V). Vertical lines connect values obtained with or without supposing water conduction by the roots of the stubble ?:higher value uncertain.

Efektiva elvaporigo el nuda tero en monataj periodoj en 1951-1958 inkl.; lizimetroj Rottegatspolder. Kalkulitaj valoroj (ΣE_R) metitaj kontrau observitaj valoroj (V). Vertikalaj linioj konektas valorojn akiritajn kun au sen la supozo ke la radikaro de la stoplo kondukas akvon. ?: plej alta valoro necerta.

computed ones. Partly due to the uncertainty how to evaluate numerically the influence of remainings of roots after harvest, the results are depicted with vertical lines. Another problem is how to handle periods in winter in which vapour transport, due to a gradient of soil temperature, is likely.

This analytical approach seems promising. Therefore all lysimeters where a waterbalance sheet for short periods can be obtained, should be used to provide the soil and crop parameters for the computed water book-keeping. Even in its first rough, approximative version, this method will enable to differentiate the yearly value R-D of not weighable lysimeters into values for smaller periods. It will also enable to compute actual evaporation anywhere for those crops and soils, of which the necessary parameters have been once for all determined.

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LYSIMETERS AND HYDRAULIC SOIL EVAPORIMETERS (1)

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SUMMARY

1. The success of lysimeter investigations of water balance formation and water movement in soil depends on the preservation, within lysimeter monoliths or soils with disturbed structure, of the hydrologic and thermal regime representative of that particular soil in situ. The simplest way of preserving this regime is to use in investigations lysimeters of large capacity.

2. Even with maximum expenditure of moisture on natural evaporation, changes in moisture storage of a definite mass of soil in the active moisture exchange layer within 24 hours amount to millesimals, or less, of the weight of that mass. That is why, when using lysimeters of large capacity, it is difficult to solve the problem of precise measurements of a relatively small change in weight (moisture storage) of a large mass of soil. The use of the existing types of mechanical scales does not ensure sufficiently accurate weighing, while the designing and use of precision scales involve the necessity of taking into account the effect of some external factors (mainly, air temperature changes) on such devices. Consideration of this effect for introducing corrections may develop into a special problem, while its elimination would require complex constructions from special materials. The use in lysimeter investigations of hydrostatic scales principle, proposed by V. A. Uryvaev in the Soviet Union in 1948, permitted to solve the problem of accurate weighing of large masses.

3. The application of hydrostatic scales principle in constructing lysimeters permits to measure changes in moisture storage of soil monoliths with high specified accuracy, irrespective of the weight and size of the monoliths, and excluding to a great extent the effect of environment (air temperature, atmospheric pressure, etc.) on the "scales".

4. The considerable size of monoliths in hydraulic soil evaporimeters and the peculiarities of the design of the latter permit to study 24-hour course of individual soil water balance elements and to use devices of this type as reference instruments in evaporation studies.

5. The State Hydrological Institute developed the following three types of hydraulic evaporimeters (a) the Large Hydraulic Evaporimeter of the Waldai Scientific-Research Hydrological Laboratory—a field laboratory installation with an underground tunnel for experimental studies of water balance formation of a mass of soil within a monolith 5 sq.m. in area and 2 m. in height; (b) forest soil evaporimeters, 3 sq.m. in area and 1.5 m. in height, which are weighed on hydraulic scales (used at the Valdai laboratory in studying 24-hour and seasonal course of evapotranspiration and transpiration of various species of trees and types of grass cover); (c) small-scale hydraulic soil evaporimeters, 0.2 sq.m. in area and 1.5 m in height, used by the network of hydrometeorological stations of the Main Hydrometeorological Service Administration.

6. The general design of hydraulic evaporimeters permits to make active experiments, creating artificial conditions of specified hydrologic and termal regime of soil monoliths. This facilitates a detailed study of the laws governing the formation of water balance of soils and the determination of the dependence of its individual elements on various factors as well as a through investigation of all processes taking place within a mass of soil.

RÉSUMÉ

1. Le succès des recherches lysimétriques du bilan d'eau et du mouvement de l'eau dans les sols dépend de la préservation à l'intérieur de lysi-

(1) The report outlines the basic provisions for lysimeter investigations in natural conditions and contains information on such investigations carried out in the Soviet Union by means of hydraulic soil evaporimeters operating on the principle of hydrostatic scales (in accordance with the Archimedés law).

mètres monolitiques avec sols présentant une structure modifiée, du régime hydrologique et thermique, représentant chaque sol particulier in situ.

Le moyen le plus simple de préserver ce régime est d'utiliser des lysimètres de grande capacité.

2. Même avec les dépenses maxima d'humidité par l'évaporation naturelle, des modifications de l'emmagasinement d'humidité d'une masse définie du sol pendant 24 heures, ne s'élèvent qu'à des millièmes et même moins du poids de cette masse.

C'est pourquoi quand on utilise des lysimètres de grande capacité il est difficile de résoudre le problème des mesures précises d'un changement relativement faible en poids de l'énorme masse du sol.

L'utilisation du type existant d'échelles mécaniques ne donne pas la certitude d'assurer une pesée suffisamment précise parce que l'emploi de ces échelles de précision suppose la nécessité de tenir compte de l'action de certains facteurs externes (particulièrement la variation de la température).

La prise en considération de cet effet en introduisant des corrections peut conduire à des problèmes spéciaux tandis que son élimination exige l'emploi de constructions plus complexes.

L'emploi dans les recherches lysimétriques du principe des échelles hydrostatiques, proposé par V. A. Uryvaev en Union Soviétique en 1948 permet de résoudre le problème de la pesée précise de grandes masses.

3. L'application de ces échelles hydrostatiques permet d'éliminer en grande partie l'effet des conditions extérieures (température de l'air, pression atmosphérique, etc.).

4. Les dimensions considérables d'évaporomètres en question permettent d'étudier le bilan hydraulique au cours d'une période de 24 heures et d'utiliser les appareils en question comme instruments de référence dans les études de l'évaporation.

5. L'Institut Hydrologique d'Etat a développé trois types d'évaporomètres qui sont décrits dans la note présentée.

The term lysimeter investigations, as used in this report, is assumed to comprise all studies of the movement of water or soil solutions within a definite mass of soil isolated by waterproofed walls and provided with a device for collecting percolation water. The success of lysimeter investigations carried out in natural conditions depends on the fulfilment of the following basic requirements.

1. Throughout the experiment, the thermal and water regime of the soil monolith or block of ground with disturbed sturcture placed in the lysimeter must fully conform to the natural thermal and water regime of the soil-ground mass under study.

2. The place of lysimeter installation on the plot under study and the location of the "evaporation surface" of the soil monolith must ensure measurements of evaporation (the principal item of moisture expenditure from soil) in exactly those microclimatic conditions which are characteristic for the natural surface under study.

3. The accuracy of lysimeter weighing must be such as to guarantee the possibility of obtaining characteristics of all minor changes in the soil moisture-storage, which may result from evaporation, irrigation of the soil surface by rains, and condensation of moisture within the mass of soil and subsoil.

The simplest way of meeting the first requirement is to use in investigations lysimeters of large capacity. Most favourable conditions for preserving thermal regime in the soil are secured in lysimeters of large dimensions, both in surface area and height. By providing lysimeter walls with heat insulating at the place of contact with soil, the disturbance of the thermal regime can be easily reduced to an insignificant border effect.

It is more difficult to solve the problem of creating natural water regime in the soil or ground placed in lysimeters, the reason being the great im-

portance of ground-air division surface for the movement of water and its seepage from soil.

A. F. Lebedev's experimental and theoretical work (1918) conclusively showed that ground-air division surface keeps back water in the ground, so that free water seeps from the ground only when hydrostatic head in the water at the division surface exceeds atmospheric pressure. Consequently, overmoistening of soil up to capillary moisture capacity must always take place at the division surface. This accounts for the disturbance of the water regime of the soil or ground at lysimeter bottom, if in natural conditions moisture percolates to a greater depth.

After A. F. Lebedev, numerous refences to the importance of ground-air division surface (or that between soils of different porosity) may be found in the works of other authors (Zunker, 1930; Richards, Neal and Russel, 1939; Kohnke, Dreibelbis and Davidson, 1940; Colman and Hamilton, 1947; and others), while L. A. Richards (1950) even formulated the "seepage law" as one of the general "laws of soil moisture". Until quite recently, however, in designing lysimeters this law has not always been taken into account.

Changes in moisture capacity and percolation conditions due to the height of lysimeters render it considerably more difficult to carry out lysimeters investigations, yet, as shown further on, there is a possible solution of this problem.

The requirement of maintaining the lysimeter surface in the microclimatic conditions (wind velocity and air humidity gradients, illumination, etc.) characteristic for the natural surface under study is not a very complicated task, but it demands a careful organization of the experiment and a design which would allow to change the position of the "evaporation surface" in height.

Until quite recently lysimeter investigations could not, in fact solve the task of studying soil-moisture storage changes in lysimeters within short periods of time, or the problem of obtaining characteristics of moisture exchange and water balance formation in a soil-ground mass within 24 hours, inasmuch as lysimeter investigations involve a study of a mass of soil approximating in size the thickness of the active moisture exchange layer, with a relatively large lysimeter sectional area (not less than 500 sq.cm.). This is evident from the fact that even with maximum expenditure of moisture on natural evaporation, changes in moisture storage of a definite mass of soil in the active moisture exchange layer within 24 hour amount to millesimals, or less, of the weight of that mass. Thit is why in using lysimeters of large capacity, it is difficult to solve the problem of precise measurements of a relatively small change in weight (moisture storage) of a large mass of soil. The use of the existing types of mechanical scales does not ensure sufficiently accurate measurements, while the designing and use of precision scales involve the necessity of taking into account the effect of some external factors (mainly air temperature changes) on such devices. Consideration of this effect for introducing corrections may develop into a special problem, while its elimination would require complex constructions from special materials. The use in lysimeter investigations of hydrostatic scales principle, proposed by V. A. Uryvaev in the Soviet Union in 1948, permitted to solve the problem of accurate weighing of large masses.

In devices based on this principle conventionally designated as "hydraulic soil evaporimeters," changes in moisture storage (weight) of the soil monolith are determined by the extent of immersion of the floating system of the device with monolith relative to the water-level in the tank in which this

system is floating (hydraulic scales). Underlying the principle of hydrostatic weighing is a physically clear equation:

$$\triangle p = \triangle h F \gamma \qquad (1)$$

where $\triangle p$ is the change in weight of the floating body, $\triangle h$ is the value of the change in the extent of the immersion of the floating system, F is the area of the floating system in the plane of floating, and γ is the density of the liquid in which the system is floating.

Measurements of weight changes on the hydraulic scales consist in determining the linear value of the floating system position on the vertical line, which may be done with great precision (to 0.01 mm. in the measuring devices employed).

Equation (1) clearly shows the dependence of the change in the extent of immersion $\triangle h$, with a change in the floating body weight $\triangle p$, on the area of the floating system F. By decreasing F it is possible to secure in the hydraulic scales a large value of $\triangle h$ with small values of $\triangle p$. Consequently, it is possible to construct hydraulic scales of high, practically any, rated absolute accuracy.

Hydraulic soil evaporimeters consist of four principal parts: the casing with the soil monolith, the floating system, the water tank, and the measuring devices for determining the extent of immersion of the floating system. The State Hydrological Institute developed three types of hydraulic evaporimeters varying as to design of these principal parts (Uryvaev, 1953).

For the purposes of detailed experimental study of the water balance of a soil mass 2 m. thick, a Large Hydraulic Evaporimeter (БРУ) has been developed by the Valdai Scientific-Research Hydrological Laboratory (Fig. 1).

The irremovable natural soil monolith of 5 sq.m. in area, 2 m. high and weighing about 18 tons is enclosed in a steel casing and placed in an under-

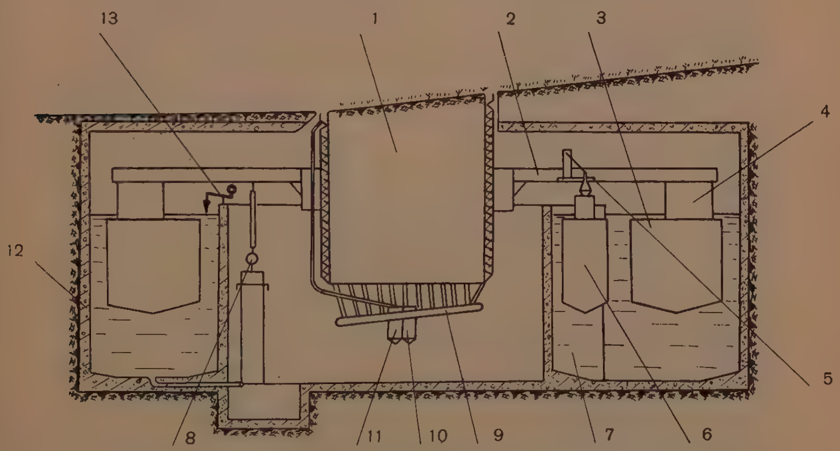

Fig. 1 Cross section of Large Hydraulic Evaporimeter. 1—soil monolith inside evaporimeter casing, 2—cantilever support claws of casing, 3—circular float, 4—circular float journal, 5—immersion recorder, 6—recorder float, 7—recorder float well, 8—system position indicator, 9—circular percolate collector pipe, 10—percolate measurements vessel, 11—surface-runoff measurements vessel connected with water collector trough, 12—circular water tank, 13—level gauge with indicator.

ground cell (Fig. 2). By means of cantilevers it rests upon the floating system in the form of a circular float-pontoon. The float-pontoon floats in a tank which surrounds the underground cell. Changes in the extent of immersion of the floating system are continuously registered by three recorders to an accuracy of 0.05 mm. of the water layer.

In addition to registering the extent of immersion of the floating system by recorders, its position may also be determined at definite hours of observation by means of three special indicators to an accuracy of 0.01 mm. Thus, the Large Hydraulic Evaporimeter, with its 40-ton total load of the floating system with monolith, records changes in monolith weight to a 50-gram accuracy.

The need for studying 24-hour and annual variations of evaporation and transpiration from various types of arboreal vegetation led to the develop-

Fig. 2 Underground cell of Large Hydraulic Evaporimeter. In the foreground, to the left, is the monolith casing.

Fig. 3 Forest soil evaporimeter. General view of installation.

ment at the Waldai Scientific-Research Hydrological Laboratory of another type of hydraulic evaporimeter—relay forest soil evaporimeter wheighed on hydraulic scales.

Irremovable natural soil monoliths of 3 sq.m. in area, 1.5 m. height, weighing about 9 tons, with arboreal vegetation (pine, fir, birch, of 13-20 years) are placed on trolleys (Fig. 3). Individual monoliths may be weighed on hydraulic scales installed separately from monoliths and representing a floating system, a tank, and a measuring device to determine the extent of immersion of the floating system at the time of weighing the monoliths.

The floating system consists of four large cylindrical floats connected by girders and a frame-cradle to which evaporimeter are rolled along rails. The floats are placed in four water tanks. As in the Large Hydraulic Evaporimeter, a system of recorders ensures the registration of changes in the weight of the monolith placed on the hydraulic scales to an accuracy of 0.05 mm. of the water layer, as well as individual measurements of monolith weight changes to an accuracy of 0.01 mm. The sensitivity of the scales is very high: a load of 60 grams causes the floating system to immerse by 0.1 mm.

In the Large Hydraulic Evaporimeter and the hydraulic scales, only the journals of loats upon which rest the cantilevers of the L.H.E. floating system, and the monolith frame of the hydraulic scales are above the water surface. The aggregate area of all float journals in the plane of floating determines the value of area F in equation (1). As pointed out above, by

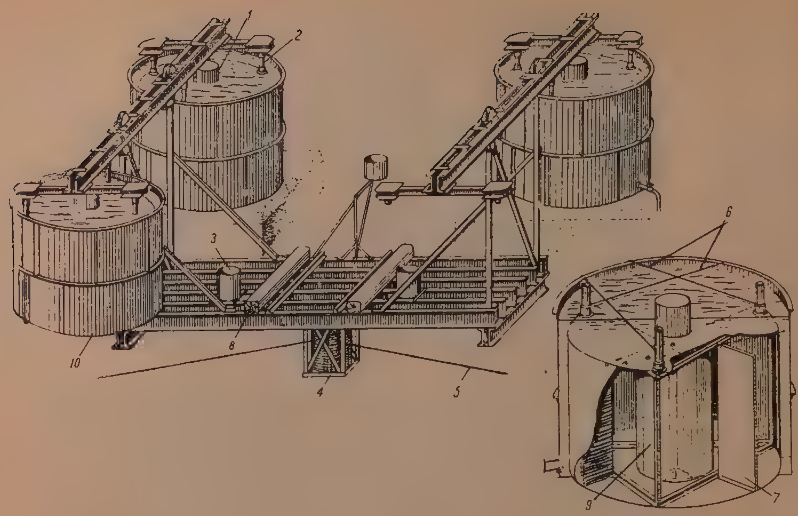

Fig. 4 Hydraulic scales of forest soil evaporimeters. 1—frame-cradle for monolith, 2—girder holding frame-cradle on floats, 3—float with internal reinforcing ribs, 4—float journal, 5—float tanks, 6—cylinder of indicator float for immersion recorder, 7—float tension wires.

decreasing the diameter of the journals it is possible to considerably raise the accuracy of weighing by these devices.

For the purposes of studying 24-hour evaporation in natural conditions in various climatic zones, a third type of hydraulic evaporimeters has been adopted for use at the network of stations of the Hydrometeorological Service: small-scall hydraulic soil evaporimeters (БРУ) (Fig. 5). Natural soil monoliths in this type of evaporimeters have an area of 0.2 sq.m. and a height of 1.2-1.5 m. and weigh 300-450 kg.

The monolith enclosed in a metal cylinder and a case is lowered into a circular float which keeps it afloat. The monolith in the cylinder with the float is placed into a metal or reinforced concrete tank installed in the ground and filled with water. The tank is covered with a deck on which is placed a layer of soil 30 cm. thick, which ensures satisfactory conditions for the growth of vegetation around the monolith.

The measuring device—a screw mechanism with a mercury contact (micrometer) and a level-gauge float—ensures measurements of moisture storage changes in the monolith to an accuracy of 0.1 mm.

In all types of hydraulic evaporimeters, measurements of the extent of immersion of the floating systems are taken in relation to the actual water level in the tank, the level being measured by a special float whose shape is identical to that of the floating system. This method of measurements excludes the necessity of taking into account the effect of the environment (changes in the temperature of the air and of the water in the tank, in the atmospheric pressure, etc.) on hydraulic scales, in such cases when this effect noticeably affects the extent of immersion of the system.

The floating system and the level-gauge float are similarly affected by the environment and, consequently, correction for the changing effect of the

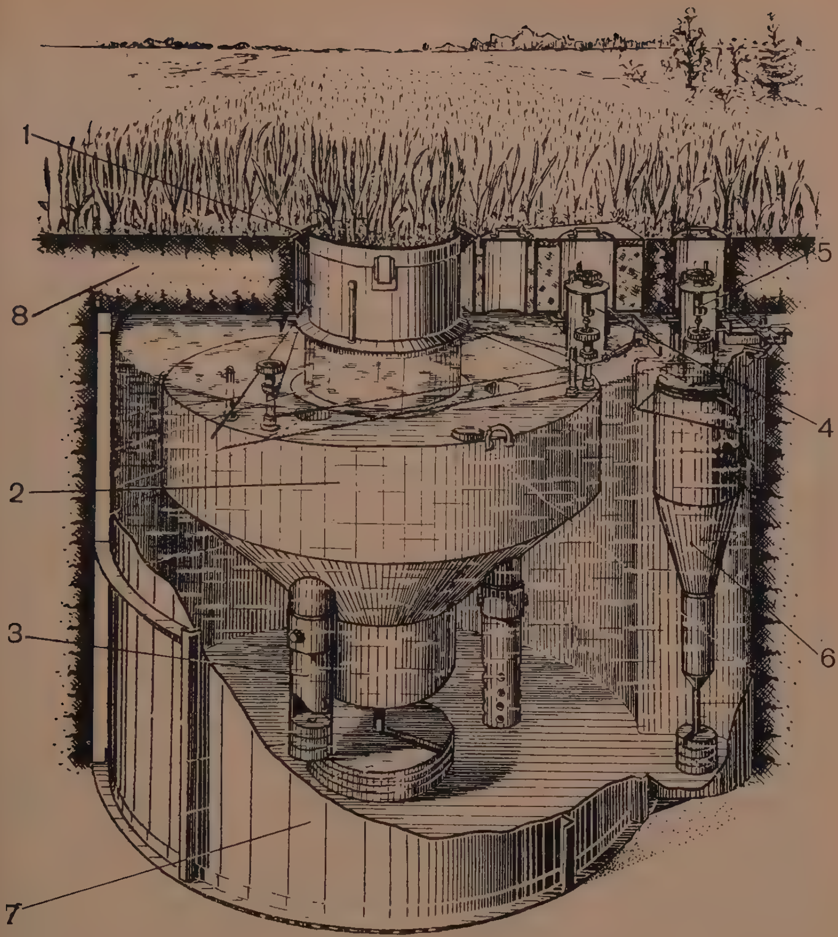

Fig. 5 Small-scale hydraulic soil evaporimeter. 1—evaporator with monolith, 2—circular float, 3—float pits with adjustment loads, 4— immersion micrometer, 5—level-gauge micrometer, 6—level-gauge float, 7—water tank, 8—soil layer on tank deck.

environment, in determining the extent of immersion of the floating system with the monolith, is introduced automatically. Moreover, the described method of determining the extent of immersion ensures correct determination of variations in the immersion of the floating system, with possible changes in the water level in the tank. The latter may occur due to water seepage through the tank walls, or evaporation. The adopted system of measurements excludes the necessity of maintaining a strictly invariable water level in the tank, which is sometimes difficult to secure in operating conditions.

It should be noted that in an earlier (БРУ) model, measurements of water level in the tank were made in a special small reservoir placed in the

soil near the evaporimeter, as is now proposed in the American floating lysimeter (King, Tanner and Suomi, 1956). Calculations and observations carried on when the earlier (БРУ) model was in operation indicated that there were considerable errors due to the overheating of the water in the reservoir. It was noted that the effect of the sun and of higher temperature in the upper layers of the soil caused an overheating of the small volume of water in the reservoir by 2-4 °C and more. With the reservoir depth of 50 cm., errors in level measurements amounted to 0.06 mm. per 1 °C.

At the same time variations were noted in the extent of immersion of the floating system of the earlier design, its weight remaining constant, due to atmospheric pressure fluctuations.

Such faults in readings should be thoroughly taken into account when measuring minor displacements of the floating system of hydraulic evaporimeters and should be eliminated through improvements in design.

The difficulties involved in evaluating the accuracy of lysimeters are due to the impossibility of making a directed comparison between the measured values of the elements of water balance in the soil monolith and the respective natural values on the plot under study.

The formation of the water balance of soil is characterized by multifactor relationships between individual elements, whose interdependence varies with weather conditions. Therefore, a complete evaluation of the accuracy of a lysimeter would require a comparison of all independently determined basic elements.

At present, it is only the amount of total evaporation that can be determined in natural conditions with relatively high accuracy, by using the heat budget method. However, this method, too, yields satisfactory results in determining 24-hours course of total evaporation only under certain conditions (absence of temperature gradients on the horizontal plane, during light wind, with continuous observations at short intervals). Consequently, the required continuous lysimeter calibration, in different weather conditions in particular, is difficult.

It should be noted that even agreement between lysimeter records and values of total evaporation measured indepentendly, for individual periods, cannot always indicate, to the representativness of lysimeter records.

Some disturbances in the conditions of water balance formation within an isolated monolith may have a mutually compensating effect. In this case equal values of total evaporation determined by lysimeter and by calculations will not characterize a possible disturbance of the natural regime of the soil in the lysimeter. For instance, equal values of total evaporation may be determined for an overmoistened monolith under conditions of overcooling and for the surrounding plot under the natural regime.

For this reason, the accuracy of hydraulic evaporimeters was evaluated primarily by the results of observations over the thermal and hydrologic regime of the lysimeter monolith soil and in situ. The absence of any disturbance of the regime is an indication of the lysimeter's accuracy. Comparison of evapotranspiration values measured by means of hydraulic evaporators and by other methods serves as an additional proof of the accuracy of the device.

During hydraulic evaporimeter tests, observations over the thermal and hydrologic regime of the soil were conducted by means of transmitters of electric resistance thermometers, thermocouples and thermistors and a transmitter of dielectric hydrometer placed into the monolith of the device and at the natural plots, as well as by measuring soil moisture.

The study of the thermal regime of the soil monolith of the Large Hydraulic Evaporimeter indicated the presence of a small heat flow from the walls and bottom of the casing to a short distance inside the monolith, in the morning. The flow is characterized by a small temperature gradient within 1 ° C (Poushkarev, 1954). In the small-scale hydraulic soil evaporimeters (БРУ), whose encased monolith is immersed in water, a minor disturbance of the thermal regime is recorded in the lowest layers of the soil. Depending on the type of the weather change, an overheating or overcooling of the soil by 1-3 ° C is observed here, as compared to the soil in natural conditions (Fedorov, 1954; Popov, 1956).

Soil-temperature regime in the monoliths of forest soil evaporimeters is studied under specified conditions, with deviations from the natural conditions on the watershed being carefully checked by additional experiments.

All of the monoliths of hydraulic soil evaporimeters are used without special heat insulation. The results of experimental work conducted by the Hydrological Institute show that, when necessary, heat insulation measures providing a plywood housing for the evaporimeter, covering the monolith with some heat-insulating material, (etc.) can ensure complete preservation of the natural thermal regime of the monoliths, permitting to specify in an active experiment the required artificial regime of heat exchange between individual layers of the monolith, by means of overheating or overcooling it inside the heat-insulating cover.

Observations of soil moisture in the monoliths of hydraulic evaporimeters showed that their hydrologic regime may be disturbed only near the bottom. When in the natural soil conditions the water table is at a depth smaller than the height of the monolith, percolation of water does not disturb the hydrologic regime of the monolith (БРУ). In other instances, percolation of water throughout the whole mass of the monolith produces overmoistening of the lower layer of soil.

In the zone of excessive moistening with easily permeable soils and small capillary ascent, a thin capillary fringe is formed below the active moisture-exchange layer, which exerts a minor influence on the formation of moisture storage in the upper part of the soil. In other climatic zones, when the monolith is installed after the discharge of spring meltwater from the soil to the depth lower than the height of the monolith and where precipitation does hot reach deep layers, the hydrologic regime of soil monoliths is the same as that of the surrounding soil throughout the whole depth of the monolith.

In order to preserve the natural hydrologic regime of soil or overlaid ground, all lysimeters should have a uniform, maximum possible layer of soil under their "evaporating surface". An overmoistening of soil and, consequently, a disturbance of the evaporation regime are to be expected in those sections underlying the "evaporating surface" where the layer of soil is less deep than the overall height of the lysimeter. Thus, the presence of air chambers or "bars" to increase the buoyancy, in the design of the American floating lysimeter referred to above should produce a disturbance of the hydrologic regime as well a change in the "effective area" of the lysimeter. An overmoistening of such sections will produce higher total evaporation from them. After the expenditure of moisture retained in the air chamber, the "effective surface" of the device will change, which is to be taken into account in making precise measurements.

It should be noted that in lysimeters there is an actual possibility of regulating the extent of soil moistening above the lower surface of the

monolith (ground-air). This may be achieved by placing a porous plate under the monolith. After the plate is saturated with the water seeping through the monolith, it is possible to draw off the water and change the extent of moistening of the lower layers of soil. Depending on the hydrologic and physical properties of soil, water from the plate is removed either by means of a vacuum pump (for sand or sandy loam) or by electroosmosis (for all other types of soils). In the latter case the removal is accomplished by means of creating a potential difference (direct current) on the metal grids placed on the upper and lower surfaces of the plate. Tests of this device on columns with sand and sandy loam soils, conducted at the Hydrological Institute laboratory, gave satisfactory results.

Results of comparative observations of the hydrologic and thermal regime of soil in monoliths and in natural conditions show that the relatively large size of monoliths in hydraulic evaporimeters of all the designs ensure almost complete conformity of these regimes.

Since 1949 the use of hydraulic evaporimeters in the study of the hydrologic regime of soil enabled the Hydrological Institute to obtain data on the 24-hour course of evapotranspiration in various zones of the Soviet Union. By using the Large Hydraulic Evaporimeter it has been possible to obtain quantitative characteristics of the hydrologic balance of soil, continuous records of the course of evapotranspiration, condensation and precipitation being provided by 24-hour recorder tapes (Fig. 6), as well as data on surface runoff and percolation to the ground-water level. These data permit to study the dependence of evaporation on individual meteorological elements, soil-moisture content, the condition and phase of the development of plants, etc. (Kozlov, 1957; Poushkarev, 1954). The large size of hydraulic evaporimeter monoliths makes it possible to carry out direct and accurate measurements of the transpiration of individual trees under conditions close to natural (Fedorov, 1957).

The general design of hydraulic evaporimeters, in which the large size of monoliths ensures preservation of the natural regime of soils, a great accuracy of measuring minute changes in monolith weight and the possibility of regulating the specified thermal and hydrologic regime of soil, all this

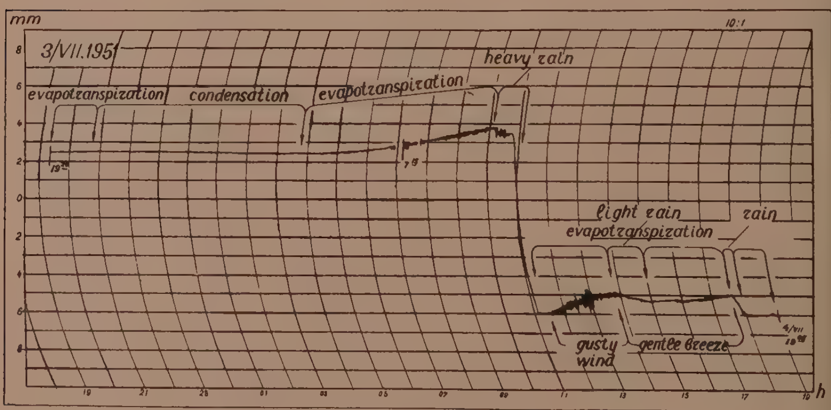

Fig. 6 Specimen of recorder tape containing data on moisture-storage changes in Large Hydraulic Evaporimeter soil monolith.

permits to conduct, with this type of lysimeter, detailed studies of the laws governing the formation of water balance of soils. Such studies facilitate the determination of the dependence of individual water balance elements on various factors, as well as a through investigations of all processes within the soil which contribute to water balance formation.

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ÜBER DEN WASSERVORRAT IN WÄGBAREN LYSIMETERN UND IN VERGLEICHBAREN, GRUNDWASSERFERNEN SANDSTANDORTEN DES NORDDEUTSCHEN DILUVIUMS

von Dr. FRIEDRICH KORTÜM, Eberswalde

ZUSAMMENFASSUNG

Es wird die Frage untersucht, inwieweit die Ergebnisse der wägbaren Eberswalder Lysimeter auf den natürlichen Standort übertragbar sind. Durch die Auswertung von Vergleichsmessungen über den Wasservorrat in verschieden mächtigen Bodenschichten grundwasserferner Sandböden am natürlichen Standort ergeben sich Anhaltspunkte über die Mächtigkeit der durch das gestützte, stehende Gravitationswasser beeinflußten Bodenschicht im Lysimeter.

RÉSUMÉ

On se propose de rechercher dans quelle mesure les résultats des lysimètres d'Eberswalde peuvent être appliqués au sol naturel. La discussion de mesures de comparaison sur la provision d'eau dans de puissantes couches sablonneuses naturelles à nappe aquifère profonde permet de trouver des indications de base sur la puissance de l'eau de gravitation maintenue dans les couches influencées d'un lysimètre.

Die prinzipiellen Einwände (Kohnke, Dreibelbis u. Davidson, 1940 u. a.), die gegen den Gebrauch von Lysimetern für das Studium der Wasserbilanz gemacht werden, sind zweifelsohne in dem Punkte stichhaltig, der sich auf das Auftreten gestützten, stehenden Gravitationswassers oberhalb des Lysimeterbodens bezieht. Wesentlich ist dabei, daß dieses Gravitationswasser die Fähigkeit erhält, den hydrostatischen Druck zu übertragen (Richards 1950, Rode 1959). Bei fortschreitender Versickerung nimmt die Schicht des gestützten Gravitationswassers entsprechend der mechanischen Zusammensetzung des Bodens zu und der hydrostatische Druck steigt an bis beim Überschreiten der Oberflächenspannung der Abfluß einsetzt.

Die Masse des gestützten Gravitationswassers weist hierbei zwei Zonen auf: die untere Zone der Sättigung, die am Lysimeterboden gestaut wird, und die obere Zone des Kapillarsaumes, dessen Wasser seinerseits von demjenigen der Sättigungszone gestützt wird. Während in der Sättigungszone eine annähernd gleichmäßige Wasserverteilung vorgefunden wird, ist diese im Kapillarsaum durch eine allmähliche Abnahme von unten nach oben charakterisiert (Rode, 1959). In den von uns benutzten wägbaren Lysimetern der Eberswalder Anlage (Lysimeter von 1 m^2 Auffangfläche und etwa 135 cm nutzbarer Tiefe; Friedrich 1930) beträgt die Masse des gestützten, stehenden Gravitationswassers bei Sandfüllung circa 58 Liter. Der Vorgang der Anstauung läßt sich bei Neufüllung eines Lysimeters zumindest quantitativ an den Gewichtsänderungen unmittelbar verfolgen. Die Dauer des Stauprozesses bis zum Wasserdurchfluß ist je nach Wetterablauf und Jahreszeit unterschiedlich und beträgt unter mitteleuropäischen Klimaverhältnissen bei vegetationslosen Böden im Mittel etwa 2—4 Monate. Die untere Sättigungszone ist in den beobachteten Lysimetern nur von geringer Mächtigkeit. Sie erreicht einige Zentimeter. Der Kapillarsaum dagegen reicht beträchtlich weiter auf-

wärts, circa 50—70 cm. Insgesamt ergibt sich für die Bodenfeuchte in unseren Eberswalder Lysimetern eine Verteilung, wie sie für sandüberlagerte Geschiebelehme und Bändertone des norddeutschen Diluviums kennzeichnend ist. Bei diesen Böden beginnt die Lehm- und Bändertonschicht in etwa 1—3 m Tiefe. Der Übergang von Sand zu Lehm ist sehr wechselnd, teils scharf ausgeprägt, teils mit allmählichem Übergang. Vetterlein (1959) beschrieb derartige Böden und beobachtete in ihnen langanhaltenden, etwa 50 cm in die Sanddecke hochreichenden Wasserstau (Abt. 87, Chorin). Für derartige Böden sind die Lysimeter-Ergebnisse direkt übertragbar. Auf den sandüberlagerten Lehmen in geringer Tiefe zeigt sich wie bei den Lysimetern eine typische zweischichtige Wurzelausbildung, indem einmal der humose Oberboden intensiv durchwurzelt ist und eine zweite Wurzelanhäufung sich in den oberen Dezimetern der Lehmschicht (entspricht der Stauzone des Lysimeters) befindet.

Für tiefreichende, grundwasserferne Sandböden sind allerdings die Ergebnisse unserer Lysimeter nicht mehr prinzipiell anwendbar, zumindest nicht für tiefer als 50 cm wurzelnde Vegetationsdecken.

Collman und Hamilton (1947) schlugen auf Grund ihrer Beobachtungen an den Lysimetern in San Dimas vor, das stehende Grundwasser aus der unteren Lysimeterzone abzusaugen.

Hierüber liegen bei uns keine Erfahrungen vor. Mit der vorliegenden Untersuchung kam es uns vielmehr darauf an, die Frage zu klären, inwieweit der Wassergehalt der Eberswalder Lysimeter in ihrer bisherigen Form dem Wassergehalt und den Wasservorratsänderungen am natürlichen Standort vergleichbar ist.

Zu diesem Zweck wurden in den Jahren 1956—1958 auf einer 25 × 50 m großen, vegetationslosen Freifläche inmitten einer 1951 angelegten Kiefern-Freikultur fortlaufend wöchentlich Bodenfeuchtebestimmungen mittels Bohrstockmethode in 7 Tiefen bis 100 cm durchgeführt. Insgesamt wurden über 5500 Proben entnommen. Die Bodenstruktur und das Volumengewicht war den Bodenverhältnissen im Lysimeter vergleichbar. Die Korngrößenverteilung ergab:

Grobsand	(Korngröße 2 —0,5 mm)	3,2 %
Mittelsand	(„ 0,5—0,2 mm)	34,3 %
Feinsand	(„ 0,2—0,1 mm)	51,6 %
Staubsand	(„ 0,1—0,05 mm)	10,8 %.

Das Volumengewicht betrug in

0— 10 cm	1,32 kg/Liter
10— 20 cm	1,41 kg/Liter
20— 50 cm	1,47 kg/Liter
50— 70 cm	1,55 kg/Liter
70—100 cm	1,58 kg/Liter

Aus dem vorliegenden Material bestimmten wir den Wasservorrat verschiedener Schichtdecken von 0—30, 0—50, 0—70, 0—100 und (durch Extrapolation) 0—135 cm Mächtigkeit und setzten diese Werte zu den Gewichten eines vegetationslosen Lysimeters in Beziehung. Zur Beurteilung des Zusammenhanges wurden die Korrelationskoeffizienten r, die Bestimmtheitsmaße B, die Regressionskoeffizienten b, die Varianzen τ_x und τ_y und die Korrelationsverhältnisse η^2_{xy} und η^2_{yx} bestimmt sowie die notwendigen Signifikanz-Prüfungen nach den üblichen Verfahren durchgeführt. Eine Zusammenstellung der statistischen Maßzahlen gibt nebenstehende Tabelle:

Mächtigkeit cm	r	B	b	τ_x	τ_y	η^2_{yx}	η^2_{xy}
0— 30	0,75	0,57	1,32	6,93	12,09	0,58	0,64
0— 50	0,77	0,59	1,02	9,09	12,09	0,59	0,63
0— 70	0,77	0,60	0,77	12,13	12,09	0,65	0,63
0—100	0,81	0,66	0,66	14,81	12,09	0,70	0,70
0—135	0,81	0,66	0,53	18,57	12,09	0,70	0,69

Die Regressionsgleichungen haben die Form

$$Y = a + b.X$$

mit Y als Lysimetergewicht und X als Wasservorrat der betrachteten Bodenschicht. Wie der Vergleich zwischen den Bestimmtheitsmaßen und den Korrelationsverhältnissen zeigt, sind die so erhaltenen Gleichungen annähernd linear sowohl in bezug auf X wie auch auf Y.

Die Prüfung auf Signifikanz hatte folgendes Ergebnis:

1. Die Korrelationskoeffizienten überschreiten jeder für sich beträchtlich den Zufallshöchstwert von 0,22, der sich aus 184 Freiheitsgraden und einer Sicherungsgrenze von 0,27 % ergibt.
2. Die Unterschiede zwischen den einzelnen Korrelationskoeffizienten liegen jedoch noch sämtlich im Zufallsbereich.
3. Die Regressionskoeffizienten sind jeder für sich signifikant von 0 verschieden.
4. Die Unterschiede in den Regressionskoeffizienten zweier aufeinanderfolgender Schichten sind durchweg gesichert.

Somit besteht eine enge, gesicherte Korrelation zwischen dem Wasservorrat der einzelnen, verschieden mächtigen Schichten des vegetationslosen Sandbodens am natürlichen Standort und dem Gewicht des vergleichbaren Lysimeters. Es handelt sich hierbei um einen echten Zusammenhang zweier Wirkungen, die durch gemeinsame, komplexe Ursachen gesteuert werden.

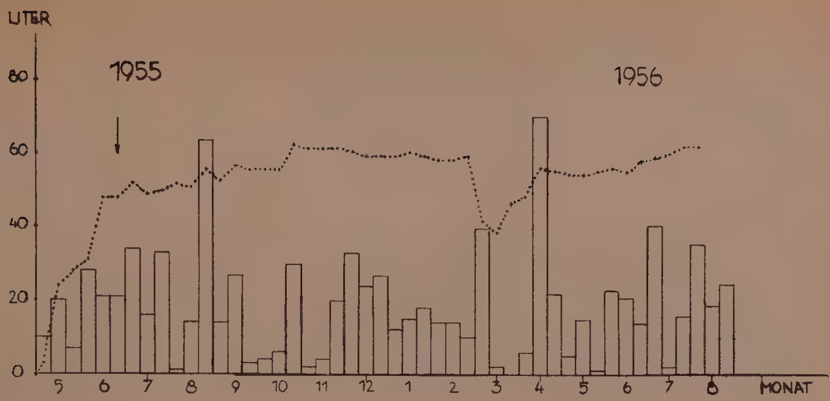
Von besonderem Interesse ist hierbei der Fall b = 1. Der Regressionskoeffizient sagt dann bekanntlich aus, daß das Gewicht des Lysimeters sich im Durchschnitt um den gleichen Betrag ändert wie der Wasservorrat am natürlichen Standort. Nun setzt sich das Gesamtgewicht (Y) des Lysimeters aus einer Reihe von Anteilen wie folgt zusammen:

Gewicht des Lysimeterbehälters und Zubehör	G
„ der Bodensubstanz im Lysimeter	B
„ des Wasservorrates der Sättigungszone	S
„ des Wasservorrates des Kapillarsaumes	K
„ des Wasservorrates oberhalb von K	H,

so daß gilt:

$$Y = G + B + S + K + H.$$

Für die Auswertung der Meßergebnisse wägbarer Lysimeter ist es bekanntlich nicht notwendig und auch schwierig, G und B dem absoluten Betrage nach zu kennen. Wichtig aber ist die Bedingung, die wohl stets erfüllt ist, daß G und B konstant sind. Die Beobachtungsergebnisse lassen nun erkennen, daß auch S und K, zumindest als Summe, weitgehend konstant bleiben. Das beigefügte Grafikon zeigt die Summenkurve des Unterschiedes in der Gewichtsänderung pro Dekade zweier vergleichbarer, vege-



tationsloser Lysimeter von Mai 1955 bis Juli 1956, von denen das eine erst Anfang Mai 1955, das andere dagegen schon im Herbst 1954 gefüllt wurde. Im erstgenannten Lysimeter begann die Auffüllung (Stauzone und Kapillarsaum), als sie im zweiten bereits abgeschlossen war. Dies wirkt sich je nach Wetterlage in einer größeren Zunahme oder geringeren Abnahme des Lysimetergewichtes pro Dekade bei dem zuletzt gefüllten Lysimeter aus. Durch fortlaufende Summierung der Unterschiede in den Gewichtsänderungen erhält man das im Grafikon dargestellte Polygon. Ferner enthält das Grafikon die Dekaden-Summen des Niederschlages in Säulendarstellung im gleichen Maßstab. Der Pfeil in der 3. Juni-Dekade gibt den Beginn des Durchflusses an. Man erkennt deutlich den zögernden Verlauf des Auffüllungsvorganges im Sommer 1955, der erst etwa im September beendet ist und im vorliegenden Beispiel etwa 58 Liter erreicht. Danach treten nur noch geringe Schwankungen um den Endwert auf. Die Unstetigkeit im März 1956 rührt von unterschiedlichen Schmelz- und Abflußvorgängen in beiden Lysimetern her und soll hier nicht weiter betrachtet werden. In niederschlagsreichen und verdunstungsarmen Perioden geht der Auffüllungsprozeß schneller vor sich. Selbstverständlich kann nicht erwartet werden, daß (S + K) streng konstant bleibt. Dies folgt u. a. auch aus dem Einfluß des Luftdruckes auf den hydrostatischen Druck des gestützten Gravitationswassers. Jedoch scheinen die Beobachtungsergebnisse darauf hinzudeuten, daß (S + K) als Summe weitgehend konstant angenommen werden kann, sofern nicht, wovon wir in dieser Betrachtung absehen, ein Aufbrauch von gestütztem Grundwasser durch die Vegetation erfolgt.

Setzen wir also zumindest für das vegetationslose Lysimeter auch (S + K) als hinreichend konstant voraus, so wird sich das Gesamtgewicht des Lysimeters ergeben als Summe aus einem annähernd konstanten Anteil C (= G + B + S + K) und dem veränderlichen Wasservorrat H oberhalb des Kapillarsaumes. Der Spezialfall, daß der Regressionskoeffizient in unseren Beziehungsgleichungen den Wert 1 annimmt, würde sodann bedeuten, daß eine Änderung des Wasservorrates X im natürlichen Boden der Schichtdicke d einer gleichgroßen Änderung des Wasservorrates H im Lysimeter oberhalb des Kapillarsaumes entspricht, wobei die Obergrenze des Kapillarsaumes vorerst noch unbekannt bleibt. Bei gleichen Bodenverhältnissen im Lysimeter und am natürlichen Standort kann man jedoch schließen, daß bei gleichen Wasservorratsänderungen auch die Mächtigkeit der hiervon betrof-

fenen Schichtdecken gleich ist, sofern die getroffenen Voraussetzungen erfüllt sind und die klimatischen Bedingungen übereinstimmen.

Unter diesen hier weitgehend erfüllten Voraussetzungen würden die gefundenen Ergebnisse aussagen, daß die Gewichtsänderungen der betrachteten Lysimeter durch die Wasservorratsänderungen der oberen etwa 50—60 cm mächtigen Bodenschicht allein bedingt sind. Das gestützte Gravitationswasser würde seinen Einfluß demnach vom Lysimeterboden etwa 70—80 cm aufwärts geltend machen. Infolge der Fähigkeit, den hydrostatischen Druck zu übertragen, bedeutet die Zone des gestüzten Gravitationswassers im Lysimeter für das von oben einsickernde Gravitationswasser offenbar eine Schicht hoher Beweglichkeit des Bodenwassers. Die Menge des am Lysimeterboden aufgefangenen Sickerwassers entspräche demnach derjenigen, mit der am natürlichen Standort unter gleichen Klima- und Bodenbedingungen in etwa 50—60 cm Tiefe gerechnet werden kann.

Diese Überlegungen gelten nur für den vegetationslosen Boden bzw. für flachwurzelnde Vegetationsformen. Es ist jedoch bekannt, daß selbst Flachwurzler auf grundwassernahen Standorten bei Feuchtemangel in der Oberschicht ihre Wurzeln in den Kapillarsaum hinabsenken. Dadurch werden die betrachteten Zusammenhänge wesentlich kompliziert.

Die durch die Beobachtungsergebnisse unter vergleichbaren Boden- und Klimabedingungen aufgezeigten Zusammenhänge finden nun eine wesentliche Stütze durch die Bodenfeuchtebeobachtungen in den Lysimetern selbst. Wiederholte Entleerungen sowie Bodenentnahmen mittels Bohrstocks ließen einen Einfluß des gestützten, stehenden Gravitationswassers bis etwa 70 cm unter Flur klar erkennen.

Zusammenfassend läßt sich für die Eberswalder Lysimeter mit Sandfüllung feststellen:

1. Die Ergebnisse (mit und ohne Vegetation) lassen sich annähernd übertragen auf Verhältnisse sandüberlagerter Geschiebelehme und Bändertone des norddeutschen Diluviums mit einer Tiefe der Lehm- bzw. Tonschicht in etwa 1—1,5 m.
2. Die Wasservorratsänderungen der vegetationslosen wägbaren Lysimeter sind ferner vergleichbar denjenigen der oberen, etwa 60 cm mächtigen Bodenschicht tiefreichender, grundwasserferner Sandböden am natürlichen Standort und erlauben somit eine laufende Überwachung des Wasserhaushaltes der oberen Schichten derartiger Böden.
3. Die Ergebnisse bestätigen die bekannte Tatsache, daß Lysimeter keine universellen Meßgeräte darstellen und ihr Einsatz daher nur unter besonderen Voraussetzungen sinnvoll ist.

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STUDIES OF GROUND-WATER BALANCE IN IRRIGATED REGIONS OF CENTRAL ASIA

by M. M. KRYLOV

1. As a result of rapid tempo in the development of irrigated agriculture in the Soviet Union, a wide scope has been obtained during the last few years by water-balance investigations. Particularly important are these investigations in the arid zone of USSR, namely in Central Asia.

2. Due to great dryness of air and to intensive ground water evaporation soils are subject in many Central Asia regions to secondary salinization: best means against this is artificial regulation of the ground water conditions. This is why the aim of water-balance investigations in irrigated regions is to elaborate forecasts for groundwater conditions and regulation thereof in needed direction.

3. In examining the dynamics of ground-water balance as an inner formation process of their regime, there arises the necessity to determine elements of such a balance; among the principal ones are the following:

Positive items:

(a) infiltration losses of irrigation waters (in canals and on fields);

(b) infiltration of superficial waters in natural water basins and atmospheric precipitations;

(c) underground discharge;

Negative items

(d) evaporation (and transpiration);

(e) underground discharge;

(f) outcrop of groundwaters.

The definition of positive and negative items of the water balance is based upon various methods among which great importance is been paid to lysimetric observations and also to a graphic method of treating data concerning the groundwater regime.

5. Lysimeters of different designs are used for determining the infiltration volume of irrigation waters, of losses on water filtration in irrigating canals, of ground water evaporation and losses of it on transpiration.

Graphic treatments of observation data concerning the range of ground water levels allows to judge about the volume of infiltration supplies of ground waters on account of atmospheric precipitations, irrigation waters, and also of the expenditure of water on evaporation and transpiration.

6. Studies of the groundwater balance serves as means of forecasting the groundwater conditions and to elaborate measures of artificially regulating the ground-water regime in reclamation work.

LYSIMETRY AT THE NATIONAL VEGETABLE RESEARCH STATION, WELLESBOURNE, WARWICK, ENGLAND

by E. J. WINTER, P. J. SALTER and G. STANHILL *

SUMMARY

Potential and actual evapotranspiration from various crops are measured regularly at Wellesbourne by means of Garnier transpirometers and small weighable lysimeters respectively.

The measurements are compared with estimates made using an extension of the Penman method, with the results of gravimetric determinations of soil moisture content, and with the measured loss from an open water surface.

The various results have been used in determining the amount and timing of watering in experiments on the irrigation of vegetable crops.

It has been shown that the amounts of evapotranspiration could differ between different vegetable crops growing under identical weather conditions. A simple method for estimating crop cover has been developed and used in modifying the Penman estimate of soil moisture deficit to apply to crops whose foliage was not fully covering the surface of the soil.

An integrating combined evaporimeter and raingauge (described in detail elsewhere) has been developed. This instrument is intended for use by growers in regulating commercial irrigation practices.

RÉSUMÉ

Les évapotranspirations potentielle et actuelle de cultures variées sont mesurées régulièrement à Wellesbourne au moyen des transpiromètres Garnier et de petits lysimètres qu'on peut peser facilement, respectivement.

Les mesures sont comparées aux estimations faites en employant une extension de la méthode Penman, aux résultats des déterminations gravimétriques du contenu d'humidité dans le sol, et à la perte mesurée d'une surface d'eau découverte.

Les différents résultats ont servi à déterminer la quantité et l'époque de l'arrosage dans les expériences sur l'irrigation des cultures légumières.

Il a été démontré que les quantités d'évapotranspiration pouvaient différer suivant différentes cultures légumières poussant dans des conditions de temps climatiques identiques. Une méthode simple d'estimation du couvert des cultures a été développée et employée en modifiant l'estimation Penman du déficit de l'humidité du sol pour être appliquée aux cultures dont le feuillage ne couvrait pas complètement la surface du sol.

Un évaporomètre integré et combiné à un pluviomètre (décrit en détail ailleurs) a été développé. Cet instrument est destiné à être employé par les cultivateurs dans les pratiques commerciales d'irrigation.

(For the purpose of this paper, the term "lysimetry" will be taken to include, in addition to methods of measuring drainage, other methods of studying changes in soil moisture status, such as field measurements or estimation of evaporation, transpiration and precipitation.)

At Wellesbourne, the water-loss from bare soil, grass and vegetable crops has been investigated, using various techniques, since 1952. Continuous records from several of the instruments to be described have been maintained since 1956. In general the policy has been to use comparatively crude and inexpensive instruments which can be adequately replicated and easily

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moved to new sites as occasion demands, instead of a smaller number of more refined and expensive instruments which often need to be set up in such a manner that alteration of site presents difficulties.

The following types of instruments have been used at Wellesbourne: —

1. Soil containers with means for collecting drainage water.
2. Weighable soil containers with or without means for collecting drainage water.
3. Evaporimeters, including evaporation tanks.
4. Raingauges designed to be relatively unaffected by wind at the time of precipitation.

Description of the Instruments

1. Six Garnier-type (1) potential transpirometers have been in regular use since 1957. Three were built two feet deep and planted with grass; three were four feet deep and planted with a different vegetable crop each year. The containers were filled with natural soil which was restored to field capacity each day by adding a measured excess of water. The difference between the volume of water added plus rainfall, and the daily drainage was taken to represent the potential evapo-transpiration of the crop under conditions when water supply was non-limiting. Poor crop growth as a result of the

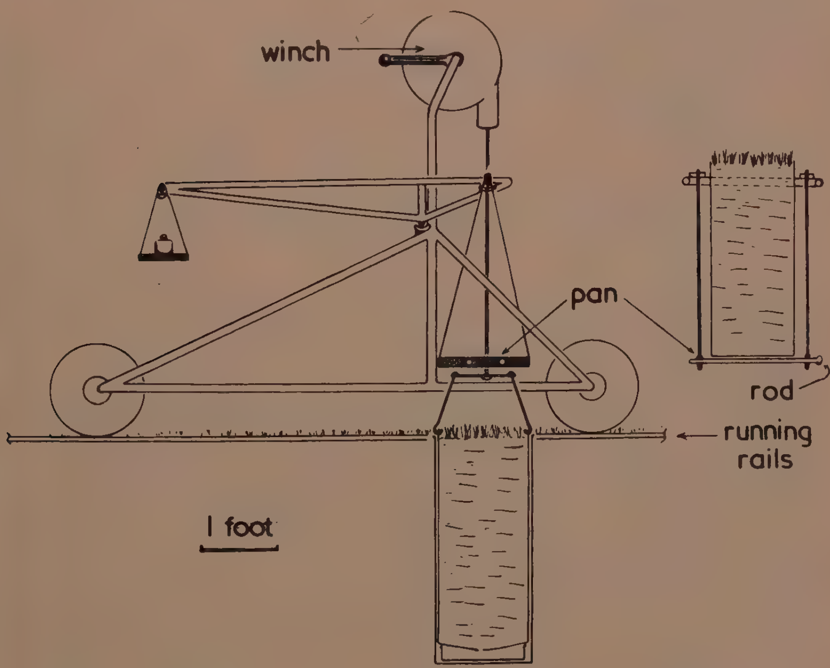

Fig. 1. Combined mobile crane and balance showing arrangement of lysimeter and method of hoisting it through frame of balance pan and supporting it on rods inserted in floor of pan. Details of construction are omitted.

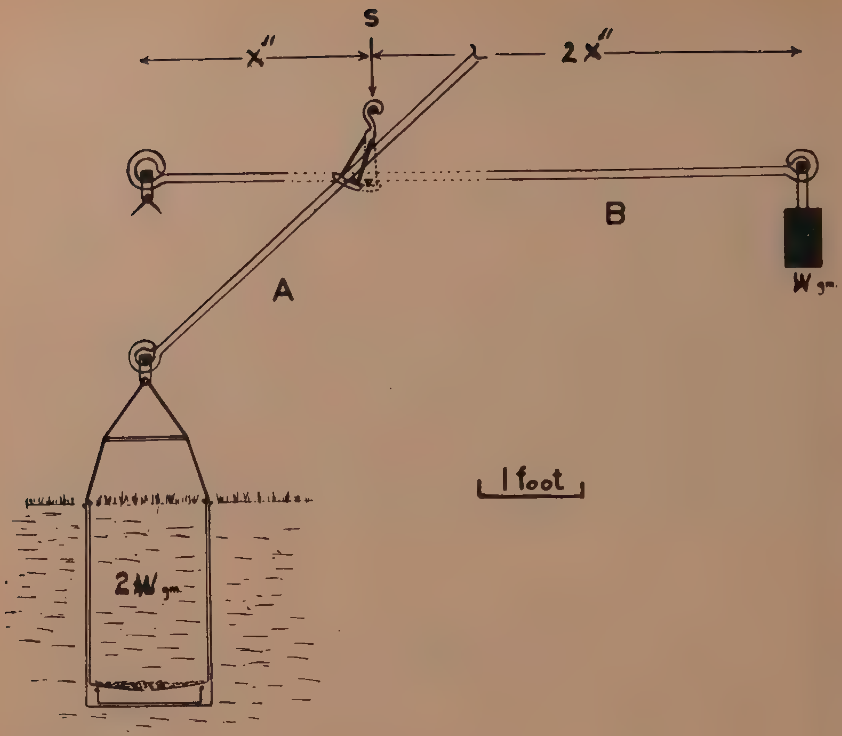

Fig. 2. Method of using lever to hoist lysimeter out of buried container (position A) and weigh it (position B). Point of suspension of whole system is at S.

daily leaching of nutrients from the soil in the containers was avoided by using the leachate as part of the water to be added to the surface.

Precautions were taken to ensure that the surroundings of the transpirometers were uniform; thus, the three grass-planted instruments were sited within the grassed area of the Wellesbourne Agro-met Station (60ft. x 30ft.) while the other three were in the centre of a nearby plot (100ft. x 60ft.) which was planted with the same vegetable crop as the instruments.

2. The weighable soil containers used at Wellesbourne ranged from small tinplate cans 3 ins. diameter by 5 ins. deep, to galvanised iron cans 11 ins. diameter by 30 ins. deep. Irrespective of size, each can was housed in a second sheathing container, slightly larger in diameter, so that the soil can could be readily withdrawn for weighing. According to the nature of the work in hand, the cans were filled with uniform soil, compost or sand, or with specially excavated monolith soil cores. Each can and its container was sunk almost to the rim in soil or other medium similar to that with which it was filled. Cans with plants growing in them were sited within adequate guard areas of the same crop. A collecting tray could be placed beneath the can drainhole and within the sheathing container. (Fig. 1).

Weighing of the smallest cans was carried out using suitable normal balances. Cans up to 1/2 cwt (approximately 10 ins. diameter and 12 ins. deep) were weighed on a two-to-one lever (Fig. 2) which was also used to lift them out of their sheathing containers. When such heavy cans were originally set up, lead weights were added to each so that at field capacity they all had the same weight and would counterbalance a common counterweight. Routine weighments were then carried out by adding ordinary brass balance weights to the can being weighed unitil it once more counterbalanced the common weight.

The largest cans were lifted from their sheathing containers by means of a mobile crane arranged to deposit the can on the pan of a two-to-one balance incorporated in its chassis (Fig. 1). The accuracy of this balance was ±5 gm., equivalent to about 1/100th inch of rain on the surface of the largest cans.

Three of the weighable monolith cores were sited on the Agro-met Station and were planted with grass, while three others were sited in the plot of vegetables surrounding the Garnier transpirometers described above. The crane and balance could be moved on rails over these cores with the minimum disturbance of the guard crop. These monolith cores were allowed

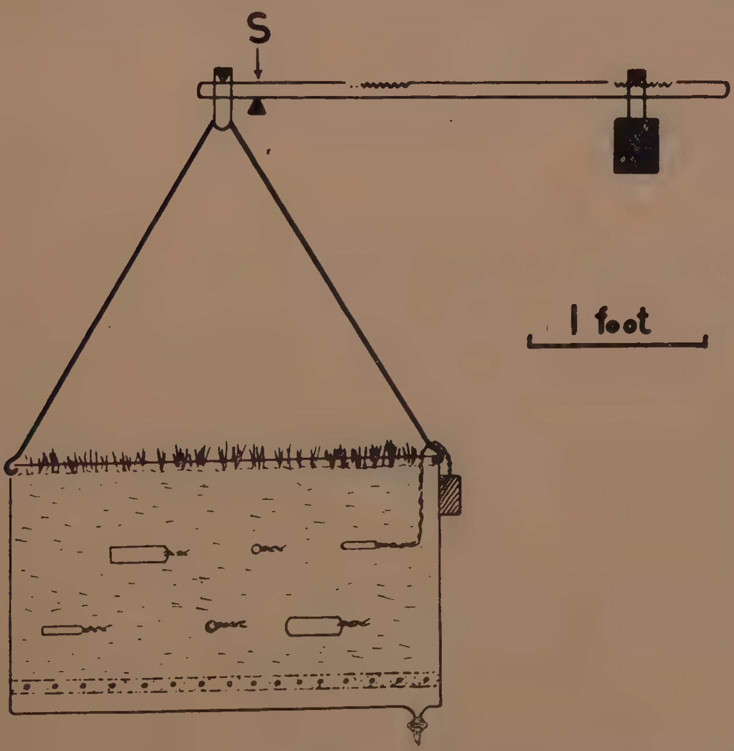

Fig. 3. Use of steelyard to suspend lysimeter tank permanently and to weigh it.

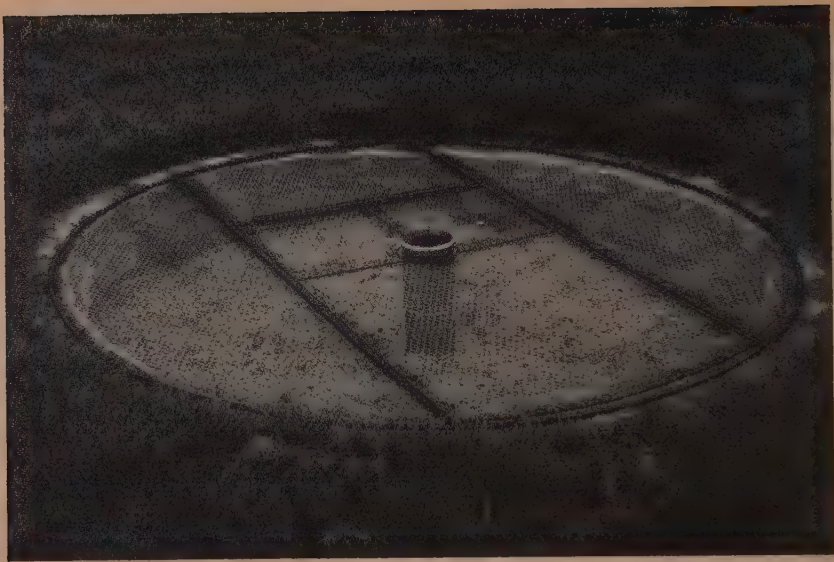

Fig. 4. 5 inch raingauge sunk in 6 ft. diameter pit, showing use of 1/2 inch wire mesh to minimise wind eddies in pit.

to receive natural rainfall only and were used to determine actual water use under natural soil moisture conditions, for comparison with the potential figure determined by the Garnier instruments and by Penman-type estimates (2).

In connection with the use of these lysimeters to measure the rate of evapo-transpiration from crops which did not completely cover the ground, the following device was used for estimating percentage crop cover. A 20-inch square angle-iron frame was supported horizontally 20 ins. above the surface of the soil. Strings stretched tightly between holes drilled in the frame divided it into 400 one-inch squares. The frame was sited at random in the crop, and the operator, standing erect, inclined his head so that his eye was positioned centrally over the frame. Without moving the head a count was made of the number of squares overlying foliage; this figure divided by 4 gave the percentage crop cover.

Fig. 3 shows a special type of weighable lysimeter comprising a galvanised metal tank having a false bottom consisting of a porous plate. The tank was filled with uniform sieved soil and was permanently slung from a steelyard which was used for its daily weighment. Grass was sown on the surface of the soil, and the apparatus was kept in a cool glasshouse. This equipment was used for comparing the performance of different types of electrode blocks for the electrical resistance method of soil moisture determination. The blocks were left *in situ* for seven months; four times during this period the moisture content of the soil in the lysimeter fell to permanent wilting point and was then restored to field capacity by subirrigation through a draincock beneath the porous plate.

3. The main evaporation tank at Wellesbourne was the standard British pattern, (6ft. square and 2ft. deep, sunk so that the water surface was at

ground level). (3).* The inside of this tank was painted black, and the water was allowed to become turbid with suspended algae in order to provide the maximum absorption of incident radiation. A standard hook gauge (British Meteorological Office reference no. 2813) was used to measure the daily variation in water level to the nearest 1/100th inch. The level of water in the tank was adjusted as necessary when it deviated more than two inches from the level of the surrounding short grass.

Other instruments for measuring the evaporative potential of the atmosphere comprised ceramic or fabric surfaces, adequately supplied with water from a container in which the level of the residual water could be measured from time to time. One such evaporimeter was coupled to a rain-collecting receiver in such a manner that the level of residual water in the receiver at any time corresponded closely with the current soil moisture deficit and with the Penman estimate thereof. This instrument has been fully described elsewhere (4) and has been marketed as an "irrigation indicator" to assist growers in deciding when to irrigate their crops, and how much water to apply.

4. In addition to the standard raingauge, ground-level gauges were installed at Wellesbourne with the object of minimising the effect of wind on rain-catch. One type consisted of a 5-ins diameter raingauge sunk so that its rim was about half an inch above the surrounding grass surface. A common coconut fibre doormat was placed round the gauge to minimise insplashing. In another instrument (Fig. 4) insplashing was prevented by sinking the gauge in the centre of a 6 ft. diameter pit. 18 ins. deep, so that its rim was at ground level. The surface of the pit was covered with half-inch wire mesh. This had the effect of almost eliminating wind eddies inside the pit.

Results

The statements below are based on observations made with the instruments described and are intended to serve as examples of the uses to which they have been put. It is not intended to discuss here the physiological or hydrological implications of the results themselves. The detailed records are available for inspection at the National Vegetable Research Station, Wellesbourne, Warwick, England.

1. Garnier Transpirometers. Over a period of two years agreement between groups of three instruments was within 5 per cent of the mean daily readings. The potential evapo-transpiration from grass was found to agree with the loss estimated according to the Penman method; the loss from a carrot crop, however, was increased as compared with the grass crop, after the soil became fully covered with foliage, (5).

2.a. Weighable containers filled with uniform compost. Agreement between replicate containers was within 5 per cent of the mean daily reading. The rate of evapo-transpiration from a crop not subsequently watered after being planted in soil at field capacity was found to be reduced when more than 40 per cent of the available soil moisture had been used. With turnip and beet the rate of evapo-transpiration was reduced after 60 and 80 per cent, respectively, of the available water had been used (6).

With a carrot crop growing in soil near to field capacity, the rate of evapotranspiration increased linearly with percentage cover until 55 per cent

(*) A U. S. Class A pan has recently been installed for comparative purposes, but results are not available at the time of writing.

of the soil had been covered with foliage; after this stage, increase in percentage cover had a progressively smaller effect on water loss, until, at 65 per cent cover, the rate of evapotranspiration was indistinguishable from that of a crop fully covering the ground. With red beetroot, there was no difference in evapo-transpiration rate between crops covering 74 per cent and 100 per cent of the soil, (7).

2.b. Weighable monolith cores. Results from three replicate instruments, over a period of two years, agreed within 3 per cent of the mean daily readings. It was found that, when the crops were growing at a soil moisture status below field capacity, the actual evapo-transpiration from grass differed from that of carrots, (8). This may be compared with the similar finding for potential evapo-transpiration obtained with the Garnier transpirometers.

3.a. Evaporimeters. During uniformity tests of six of the prototype irrigation indicators their readings were within half an inch soil moisture deficit of one another, of the Penman estimate, of the actual deficit as determined with the weighable monolith cores (2b above) and of the results of gravimetric determinations on soil samples.

3.b. Evaporation tank. Over a period of two and a half years, the total variation between daily evaporation values and the Penman estimate of water loss from an open surface was ten per cent.

4. Raingauges. Annual rainfall measured with the ground level gauge (with "doormat" protection against insplashing) was found to be 5 per cent more than that measured with the standard gauge having its rim 12" above ground. Over a ten month period, rainfall measured with the pit gauge was $2^1/_2$ per cent more than the standard measurement. Snowfall was not included in this comparison.

Discussion

However desirable from the point of view of applying statistical treatment to their readings, the replication of lysimeters is usually reduced to a minimum on account of their cost and bulk. Nevertheless, an ever-present danger in the use of lysimeters and similar instruments is the possibility of unsuspected small leaks arising. The use of comparatively cheap equipment at Wellesbourne has enabled sufficient replication to be used to make the occurrence of a leak immediately apparent. This is especially important with vessels buried in the soil or housed in underground chambers where they may be liable to corrosion or to fracture caused by freezing of their contents. For example, leakage from minute cracks in the soldered joints of drainage collecting vessels was readily detected by means of the threefold replication system at Wellesbourne, as well as occasional fracture of lysimeter drums, caused by settling of the backfilled soil around them.

Evaporation tanks, partly because of their bulk, are not usually replicated. At Wellesbourne, a leak in a concrete evaporation tank caused by frost during the previous winter became apparent because of persistent discrepancies between its readings and the Penman estimate; this however, implies acceptance of the hypothesis that two should be identical, and a small leak of this nature could go undetected for a long while.

Cross-checking of results obtained by different methods is probably the best way of determining whether the equipment is working properly. A convenient datum point which can be derived using most of the methods described is the moisture content of the soil expressed as a percentage of the

dry weight. This can, of course, be readily determined absolutely using soil samples, provided that standard conditions of time and temperature are observed during the drying process.

Knowing the soil moisture characteristics, i. e. field capacity, permanent wilting point and apparent specific gravity at representative depths (6-inch depth increments have been found to give a satisfactory overall picture), it is possible to arrive at an estimate of the current soil moisture percentage in the upper layers from the deficit calculated according to the Penman method. Thus the Penman estimate may be checked against the results of gravimetric determinations of the moisture content of soil samples.

Similarly, estimates of soil moisture deficit deduced from the loss in weight of monolith cores may be checked using soil samples withdrawn from representative cores. However, the holes left by the sampling must be carefully refilled with comparable soil and it is undesirable to carry out such sampling more than once or twice in a season, because of the damage to the structure of the cores.

Mention has been made of certain modifications to the Penman method of estimating soil moisture deficit which have been developed using the instruments described. These modifications were found to be necessary when using the Penman method for determining the amount of irrigation required for vegetable crops which, for a considerable part of their field life, do not comply with two of the basic requirements of the original formula, namely that the soil must be uniformly covered with green vegetation, and that water supply must be non-limiting.

The water loss from the plant/soil system is a variable proportion of the loss from an open water surface calculated according to the Penman method. The proportion depends upon the season of the year, the percentage of the soil surface covered by foliage, and, if crop cover is incomplete, the accumulated soil moisture deficit since the soil surface was last wetted by rainfall or irrigation, or since it was disturbed by cultivation. Fig. 5 shows graphs which have been used successfully to determine the amounts of day - to - day irrigation to be applied in experiments on the irrigation of vegetables in different parts of England. The success of the method has been assessed by comparing the calculated soil moisture deficit with the actual deficit determined gravimetrically from soil samples taken at intervals during the growing season. The average variation was found to be of the order of half an inch of soil moisture deficit.

During the course of this work, discrepancies were noticed between the amounts of rainfall collected by the standard raingauge with its rim 12 ins. above short grass, and the rainfall deduced from evaporation tank readings. It is well established that the rain catch in a normal cylindrical gauge falls with the height of the gauge above ground, and that this is associated with the increase in wind speed with height above ground, (9). Some correlation was established at Wellesbourne between the run of wind measured in miles per day, and the magnitude of the difference between rain catch in a standard gauge and in the ground level gauge surrounded by a doormat, (10). However, wind speed at the time of precipitation is not likely to be closely correlated with the run of wind over the corresponding 24 hours, and further work on this subject must await the installation of a suitable recording anemometer and recording raingauge.

In the installation described in this paper, emphasis has been placed on following a number of different approaches to the same end result, namely the assessment of soil moisture status. This has been made possible by using

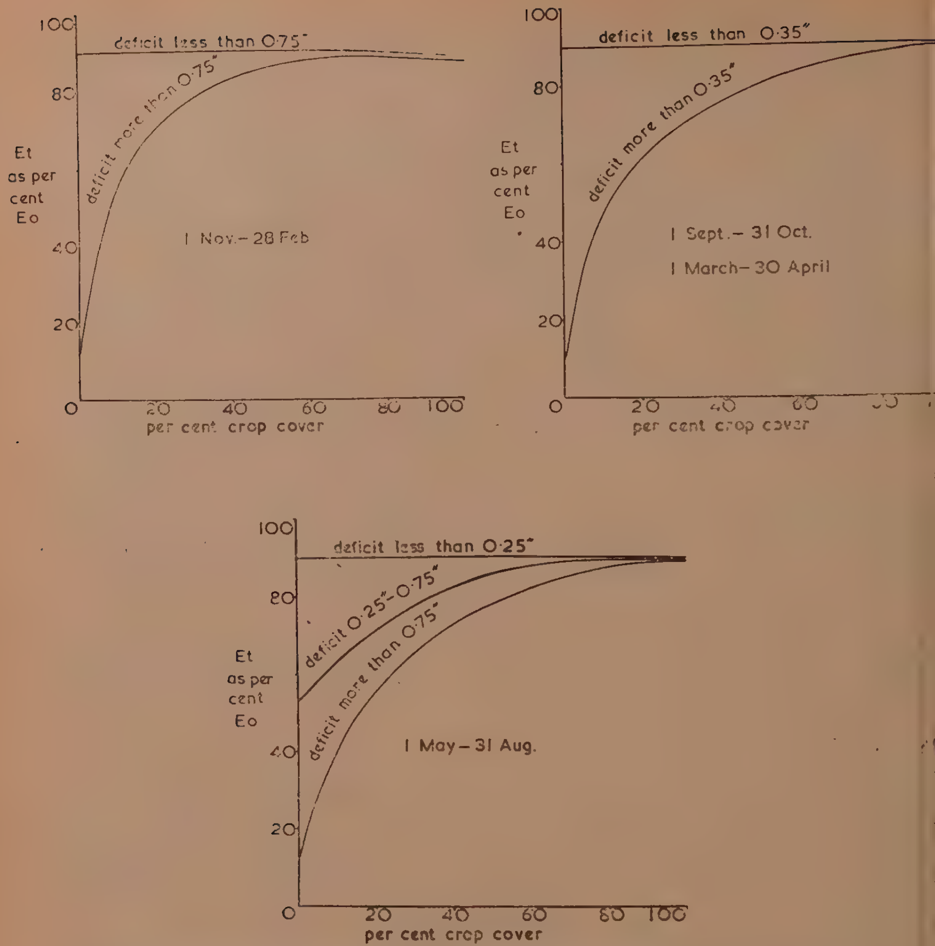

Fig. 5. The actual evapo-transpiration (Et) expressed as a percentage of the Penman loss from an open water surface (Eo) at different seasons of the year and for different percentages of crop cover of the soil.

simple and relatively inexpensive equipment with as much replication as practicable. Any errors, breakdowns or faults in design become apparent by reason of differences between individual results and the general picture given by all the instruments collectively, and it is considered that this advantage outweighs the disadvantage that comparatively crude equipment of the type described is unlikely to yield as accurate individual measurements as more complicated and expensive instruments.

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LYSIMETER TESTS IN AUSTRIA

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SUMMARY

This report deals with water cycle values (precipitation, percolation, evapotranspiration) obtained in "filled in" and "monolith" type lysimeters at the station Petzenkirchen.

The question of the correlation between evapotranspiration measured by lysimeters and evaporation rates measured with the Ramsauer evaporation meter is also discussed.

At a lysimeter filled in in 1939 with the soil type loam (area 1 sqm., depth 1.40 m), with grass-cover, average evapotranspiration during the growing seasons of the period 1948/50 accumulated to 647 mms, when the ground water table was artificially held at a depth of 40 cms. In a second lysimeter the ground water table was not artificially corrected. In that case evapotranspiration diminished by 20 per cent.

In 1952, three monolith lysimeters were set up with the soil type "colluvial brown soil" (loam) and a permanent grass cover (area 1 sqm., depth 1.30 m). They are weighable with a tolerance of 100 g (0.1 mm water column). The soil is directly placed on the bottom steel plate. During the vegetation periods 1953/58, average amounts received in three repetitions at a mean precipitation of 500 mms were: evapotranspiration 590 mms and mean percolation 50 mms, i. e. a coefficient of percolation of 0.1.

Besides describing the natural water cycle on the surface of the lysimeter soil and in it, this article also contains information regarding chemical analyses of the percolated water and, more especially, details of losses of nutrients after a potash fertilization and previous lysimeter experiments; and the heat economy in the lysimeters is compared with that in the adjacent soil.

RÉSUMÉ

On représente les grandeurs d'économie hydraulique (hauteur de précipitation, hauteur d'infiltration, hauteur d'évaporation — transpiration) déterminées sur des lysimètres « remplis » et « monolithe ».

On traite la question du rapport corrélatif de l'évaporation—transpiration déterminée à l'aide des lysimètres et de l'évaporation constatée à l'aide de l'appareil évaporatoire de Ramsauer.

Dans le cas d'un lysimètre rempli de limon en 1939 (1 m² de surface, 1,4 m de profondeur) et qui était recouvert d'herbes, l'évaporation—transpiration dans la période de végétation se montait en moyenne pendant les années 1948 à 1950 à 647 mm, si le niveau de la nappe d'eau souterraine était tenu artificiellement à 40 cm de profondeur. Chez un second lysimètre on n'a pas tenu de niveau de la nappe souterraine. De cette manière l'évaporation—transpiration s'est diminuée de 20 %.

En 1952 on a installé trois monolithes-lysimètres du type de terrain « terre brune colluviale » (limon) avec une couverture d'herbes continue (surface de recueillement 1 m², profondeur 1,30 m). Ils sont pondérables à 100 g près (= 0,1 mm d'hauteur de précipitation). Le fond repose directement sur la plaque de recouvrement. Pour les années 1953 à 1958 la hauteur d'évaporation moyenne se montait à 590 mm, l'infiltration moyenne à 50 mm, d'où le coefficient d'infiltration 0,1, et ceci dans la période de végétation, pour trois reprises et une hauteur de précipitation moyenne de 500 mm.

En dehors de l'économie hydraulique naturelle sur et dans le sol du lysimètre, on décrit des résultats de recherches chimiques de l'eau d'infiltration, en particulier les pertes de substances nutritives après engraissement au potassium, on discute des essais de lysimètre plus anciens, et on compare l'économie de chaleur du lysimètre avec celle du terrain environnant.

Introduction

The first Austrian lysimeter tests were carried out at the time of the old Austro-Hungarian monarchy (before 1918). Even at that early date the Ministry of Agriculture promoted such tests regarding the water cycle of cultivated soils and the first articles describing lysimeter tests were published in the official weekly of the Imperial Ministry of Agriculture in Vienna in 1870, in the periodical of the Austrian Society for Meteorology (1871) and in the Magazine for Agricultural Experimentation in 1898.

All these articles concerned themselves exclusively with the questions of quantity and quality of percolation and with the water cycle of soils with various vegetative covers.

Up to 1949 "filled in" lysimeters were the only ones in existence.

Trials with weighable lysimeters were started shortly before the second World War, and led up to the introduction of monolith lysimeters in 1952.

This present publication aims at giving a short review of earlier lysimeter tests carried out in Austria, as well as a description of more recent results achieved in the stations of Petzenkirchen which are managed by the Federal Experimental Station for Agricultural Engineering and Soil Science upon request of the Federal Ministry of Agriculture and Forestry.

Austrian Lysimeter Tests 1869—1958

Table 1 contains the most important data regarding Austrian lysimeters in chronological order, it may serve as a supplement to the Table published by Kohnke, Dreibelbis and Davidson (1), an excellent complete bibliography of lysimeters existing in the whole world up to 1940. (Numbers in brackets are referring to the bibliography).

This table shows that, in older lysimeters, relatively small quantities of soil were *filled into* containers of various surfaces and depths. It is impossible to get results from such filled in soils, the structure of which has been disturbed (data regarding percolation, evaporation, quality of percolated water), identical with those achieved under normal conditions. For this reason the exclusive use of monoliths was decided upon in 1952, i. e. that of soils the natural structure of which has been preserved. In this way it is possible to avoid an important source of errors which is the disturbance of the natural structure of the soil, while it is unfortunately impossible to eliminate disturbances caused by the technical gadgets necessary for the measurement of weight, percolation and temperature of the soil monoliths, and by their extraction from the soil.

The reason why lysimeter tests are carried out all over the world in spite of these difficulties, is that they are shedding light on that part of the water cycle in the soil, including the losses of nutrients by percolation, which is most difficult to assess, and such experiments may therefore be considered as an important supplement to large scale research embracing whole areas.

I. Lysimeter Experiments in Salzburg and Oberdöbling

The first Austrian lysimeter tests were carried out by Prof. *Woldrich* in 1869 in Salzburg and Oberdöbling near Vienna (2,3). In these tests 5 zinc metal sheet tubes (diameter 18.5 cms) of different lengths (16, 32, 63 and 126

TABLE 1

Data on experiments with lysimeters in Austria 1869-1958

Investigator	Location	Year of instal-lation	Soils	Num-ber of Lysi-me-ters	Lysimeter construction						Filter material etc.
					Type	Shape of surface	Dimensions		Material		
							Area m²	Depth ms	Walls	Bottom	
Woldrich	Salz-burg,	1869	Sandy loam, loam, sand	5	Filled-in	Round	0,027 0,027 0,027	0,16 0,32 0,63	Zinc		Sieve
	Ober-döbling	1869						1,26			
Hanamann	Lobositz	1896	Loess loam, Plaener calcar-eous soil, Basalt earth, Brown arable soil	9	Filled-in	Square	0,1	0,5	Metal	Per-forated	
Donat Fischer Güntschl Ramsauer	Petzen-kirchen	1939	Loam	2	Filled-in	Square	1,0	1,4	Sheet steel	Sheet steel	Gravel filter and perforated ironpipes
Ramsauer	Fußach	1948	Gleyed, gray river side soil (silty, clay loam)	3	Monolith	Square	0,25	1,0	Sheet steel	Per-forated steel plate	working; at 30, 60, 90 cms depth ground water table
Feichtinger Ramsauer Schleifer	Petzen-kirchen	1952	Colluvial brown earth, loam	3 (3)	Monolith	Square	1,0	1,3	Sheet steel	Per-forated steel plate	working; 3 reserve lysimeters
Hydrogra-phische Landes-abteilung N.Ö.	Ober-sieben-brunn	1957	Riverside soil, wind blown soil, Chernozem soil	4	Monolith	Square	0,25	0,75	Sheet steel	Sheet steel perforat-ed and sieve	working

cms) were vertically inserted into the soil, and from their bottom ends the percolation water dripped through sieves and was sucked off by a second tube of a diameter of 2.6 cms, and could then be measured in a graduated container. The tubes were filled with sandy loam, loam and sand, and were exposed to natural atmospheric conditions.

Woldrich compared these specific percolations with the amount of precipitation, with the four different depths of percolation, with the type of the soil, as well as with that of the vegetative cover (fallow soil or vegetation) in the respective months and seasons. This study of the distribution of the soil water after precipitations during the individual months and seasons, with or without vegetation, gave interesting results. Thus the considerable differences in the amounts of percolation water showed the great influence of the vegetation upon the amount of evaporation, and comparisons were made between percolation results in forests and those on grassland from which conclusions could be drawn in view of the more or less great abundance of springs.

However, the author states that "results achieved by this type of experiments can give no more than approximate values of the actual infiltration of precipitations into the soil, as conditions in the soil may be different within the walls of the tube from those outside them, and it might therefore be preferable to use wirenet grit walls; however, a comparison of the water dripping from the bottom end of it would then not be possible because, under such conditions, water from the sides would naturally infiltrate and falsify the amount of precipitations collected on the surface of the tubes."

II. Lysimeter Experiments in Lobositz

While Prof. Woldrich was, in this test, mainly concerned with water economic questions, Dr. *Hanamann* carried out lysimeter experiments of several years' duration (1896-1900) in the Prince Schwarzenberg Experimental Station in Lobositz (now Czecho Slovakia) which served the purpose of finding the exact values of losses of nutrients caused by leaching (4,5). He used 9 metal lysimeters of a square surface of 0.1 sqm and a depth of 0.5 m with a sloping perforated bottom and a glass container.

These lysimeters were filled with 50 kgs of brown arable soil each. The first 6 boxes were filled with "alluvial brown soil". One of them was left without vegetation, the other 5 were planted with various field crops. The remaining 3 boxes were filled with loess loam, Plaener calcereous soil and basalt soil and had no vegetation.

These tests served the purpose of discovering the "*differences in the leaching of salts*" from various non-fertilized, fallow and cultivated soils. The extent of losses of 15 different elements, such as nitrogen, lime, sodium, potash, phosphorous, by leaching in fallow soil or where red clover, rape, barley, horse beans, wheat, sugar-beets, corn were cultivated, were carefully registered.

Dr. Hanamann found that precipitation washed out far more plant nutrients from fallow soils than from cultivated ones, and that soils are impoverished if they are left untended. Lime is more easily leached out than all other nutrients.

III. Lysimeter Experiments in Petzenkirchen Main Station

In 1939, the first lysimeter station with weighable lysimeters was on the initiative of Min.-Rat Dr.-Ing. Ramsauer jointly set up in Petzenkirchen by

the Agricultural University (Prof. Dr. Fischer, Prof. Dr. Donat) and the Federal Ministry of Agriculture and Forestry (Reg.-Rat Dr.-Ing. Güntschl).

Installation

Loam was illuviated into two lysimeters of a depth of 1.40 mts and a square surface of 1 sqm. The percolation water dripped through a 90 cms deep layer of loam into a 0.5 m deep gravel filter of coarse sand, and from there by perforated iron tubes into the container. The lysimeter box was made of sheet steel plate.

Illustration 1 shows at the left lysimeter I, with well developed grass cover, and at the right lysimeter II with an inferior grass cover. While lysimeter I allowed for the study of the water cycle under natural conditions, lysimeter II was provided with a ground water table which was, for 12 years, artificially held at a level of 40 cms; this ground water table was controlled by a communicating glass tube. This was the reason why no healthy crop of grass was able to develop in years of heavy rainfalls. Daily measurements were made in each lysimeter of changes in weight, percolation at the depth of 1.40 mts, and soil temperatures. Evaporation values were calculated.

On the lefthand side of figure 1 shown at the foot of this page one can see the rails of the transportable scales which are, for purposes of weighing, moved on top of the lysimeters. By help of supporting hocks (see fig. 3) the monoliths are lifted and weighed with a tolerance of a water column of 0.1 mm.

For 12 years these lysimeters were under a permanent grass cover, and were horizontally installed.

Fig. 1 Lysimeter in Petzenkirchen Main Station and mountain rain gage 500 sq. cms.

Meteorological Equipment

1 mercury thermometer 2 mts above ground level
1 thermohygrograph 2 mts above ground level
1 minimum thermometer 2 mts above ground level
1 minimum thermometer at ground level
6 soil thermometers at ground level and at 5, 15, 30, 50, and 100 cms below ground level in the adjacent soil
5 soil thermometers at ground level and at 5, 15, 30, 50, and 100 cms below ground level in lysimeter I
5 soil thermometers at ground level and at 5, 15, 30, 50, and 100 cms below ground level in lysimeter II
1 polymeter (Lambrecht) 2 mts above ground level
1 snow board for measurement of thickness of snow cover
2 rain gages for use in mountainous areas (500 sq. cms) at ground level and 1 m above
1 rain recorder 200 sq. cms at 1 m above ground level
1 evaporation scale (Wild) 1 m above ground level
3 evaporation meters according to Ramsauer at ground level and at 1 and 2 mts above ground level
1 dew recorder according to Kessler-Fuess
1 sunshine autograph 1 m above ground level
1 anemometer 1 m above ground level

Soil

When the soil was examined at the end of the experimental period, it was found that an A horizon (mull humus) had developed at a depth of 0 to 10 cms, while there was fine sandy loam to loam at a depth of 10 to 90 cms, and underneath this a substantial layer of sandy gravel and pebbles.

It is interesting to note that, in lysimeter II, during this 12 year period, due to the influence of the constant ground water table, a B(G) horizon with rusty spots had developed at a depth of 45 to 90 cms. Reduction spots were, however, not only present at a depth of 45 to 90 cms, but also above that layer at a depth of 12 to 45 cms and even at a depth of 12 to 45 cms, obviously as a consequence of the continually high percentage of soil moisture. The mixture of humic materials caused by soil animals was also much less pronounced in lysimeter II than in lysimeter I.

Aim of the experiment

Main aim of these tests was the discovery of the difference of the water cycle in loamy soils with a constant ground water table at the depth of 40 cms, and loamy soils which rest, at the depth of 90 cms, on a permeable strata.

Percolation

Percolation figures given in Table 2, referring to 1950, are showing periods of high percolation and periods of consumption and storage. The dependence of the amount of percolation on the degree of soil moisture in both lysimeters is clearly visible.

In winter percolation was retarded by the slow thawing of the snow cover, while in summer percolation took place only at times of heavy

TABLE 2

Precipitation and percolation in lysimeters I and II in 1950 in mms

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Precip.	65	41	25	69	24	15	92	55	146	82	117	27	758
Percol.:													
Lys. I	62	42	16	18	.	.	.	.	.	.	58	20	216
Lys. II	58	10	13	51	.	.	8	.	80	50	122	23	415

precipitation. Twice as much water percolated in the constantly damp lysimeter II than in lysimeter I, a fact which is also proved by the coefficients of percolation given in Table 3. Lysimeter II stored during the autumn and winter hardly any water at all, while lysimeter I stored, or used up, approx. 40 per cent of the entire precipitation.

These differences were still grater during the vegetation period: In lysimeter I approx. 80 per cent of the precipitation were used up, while in lysimeter II no more than 50 per cent were consumed.

Evaporation

The comparison of evaporation values (see Table 4) of lysimeters I and II (constant ground water table at a depth of 40 cms) shows striking differences between evaporation values of the two lysimeters during dry periods in summer. In 1950, this discrepancy increased from 70 per cent during the month of June to 111 per cent during August. In other words, the difference in the dampness of the soil was of considerable influence upon the amount of evaporation during the dry periods.

Table 5 gives data regarding the distribution of evaporation during the vegetation period, and during the remaining months of the year. This table shows the considerable influence of the vegetation period upon the amount of evaporation.

On the average, evaporation during the vegetation period (IV—IX) was approx. 6 to 7 times higher than during the rest of the year. The ratio of evaporation during the vegetation period and evaporation during the rest of the year was approx. the same in both lysimeters. On the other hand, total evaporation in lysimeter II amounted to 821 mms in 1950. In lysimeter I (no ground water table) evaporation amounted to 597 mms, i. e. 79 per cent of the total precipitation. Percolation as well as evaporation showed a considerable increase in lysimeter II due to the additional water supply.

TABLE 3

Coefficients of Percolation for the period 1947/50

Lysimeter	IV—IX	I—III, X—XII	Year
I	0.21	0.57	0.35
II	0.48	1.00	0.70

1) Evapotranspiration of Lysimeters in mms

Lysimeter I: 0— 90 cms illuviated fine sandy loam (loam)
90—100 cms coarse sandy gravel (filter)
Lysimeter II: like I and constant ground water level at 40 cms depth

Year	Lysimeter	evapotranspiration in mms														
					vegetation period											
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year	IV—IX
1947	I	snow			56	102	83	119	79	47	17	4	12		486
	II				57	144	88	136	120	98	40	5	9	—	643
1948	I	4	44	34	61	90	71	107	106	74	15	10	7	623	509
	II	5	49	36	76	148	78	114	126	89	16	11	9	757	631
1949	I	3	7	16	52	101	119	94	110	52	33	4	4	595	528
	II	5	9	18	54	112	137	99	115	59	37	1	2	648	576
1950	I	4	11	25	54	153	83	99	78	49	24	9	8	597	516
	II	4	19	31	61	158	141	152	164	60	21	6	4	821	736

I average of 1947/1950	510
II average of 1947/1950	647

2) Precipitation in mms

Year	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year	IV—IX
1947	33	23	25	31	30	84	61	50	7	13	130	123	610	263
1948	91	109	65	13	51	119	166	120	48	49	16	14	861	517
1949	67	10	38	54	153	82	152	330	46	19	103	72	1126	817
1950	65	41	25	69	24	15	92	55	146	82	117	27	758	401

average	500

TABLE 5

Distribution of evaporation over the year

Year	Lysimeter I		Lysimeter II constant ground water table at 40 cms	
	Vegetation period	Month I—III, X—XII	Vegetation period	Months I—III, X—XII
1948	82 %	18 %	83 %	17 %
1949	89 %	11 %	89 %	11 %
1950	86 %	14 %	89 %	11 %
Average	86 %	14 %	87 %	13 %

Losses by leaching

Losses in phosphates were unimportant, those in nitrogen, on the other hand, were considerable, as compared with average fertilization. The quantity of iron-compounds which was leached out was comparatively great.

Because of the disturbance of the original structure of the soil when it was transferred to the boxes in 1951, this lysimeter station was given up and replaced by the station in the Petzenkirchen Plant Protection Garden.

IV. Lysimeter Experiments in Fussach

3 lysimeters, monoliths consisting of gleyed gray riverside soil (silty clay loam) influenced by a permanent ground water table of 30, resp. 60 and 90 cms depth, continually under grass since 1948, were set up within the framework of the water economic trials for the amelioration of the Vorarlberg Rhine valley on the lake of Constance. Even though—because of the method used for the measurement of water consumption—values registered since 1948 may be considered as no more than approx. values for the evaporation at different depths of ground water tables, they are clearly showing the importance of the degree of the soil moisture for the process of evaporation.

V. Lysimeter tests in the Petzenkirchen Plant Protection Garden

Experiments carried out by B. Ramsauer in collaboration with F. Feichtinger and H. Schleifer in 1952, in which monoliths in weighable lysimeters were used for the first time, were totally different from previous experiments (see Fig. 2).

TABLE 6

Average annual evaporation of lysimeters during the period 1948/58 in mms. Average annual precipitation 1149 mms

		Evaporation
Ground water table	30 cms deep	659
—"—	60 " "	455
—"—	90 " "	405

Fig. 2 Extraction of monolith lysimeter.

Aim of experiments

The aim of this particular experiment is the examination of the water cycle of colluvial brown soil under a cover of grass, thrice repeated, and clearing up the question whether results achieved by measuring evaporation with the Ramsauer evaporation meter and results found by lysimeters can be correlated.

Installation

The station has, at present, three horizontally arranged lysimeters of a square surface of 1 sqm and a depth of 1.30 mts. There is room for three more lysimeters. The bottom plate is perforated and two sloping groves are serving its drainage. The monolith rests immediately upon the bottom plate of the lysimeter. No arrangements were made for a filter layer in between. The original idea was to produce in the lysimeters a degree of soil moisture similar to that outside their walls by the insertion of three porous ceramic pipes.

There are seven plugs in the walls of the lysimeter (fig. 4) which can be unscrewed to allow for the introduction of instruments for measuring the soil moisture and temperature. Glass windows were inserted through which the soil profile and its possible changes (for inst. due to frost) can be observed. A plate rim surrounding these windows which is rammed into the monolith prevents percolation along the window panes.

Soil temperatures recorded at 44 points can be read off an electric recorder. A temperature recorder allows for continuous comparison of temperatures in the lysimeters and in the adjacent soil. Splash screens are arranged around lysimeters so as to prevent water from the outside from splashing onto the surface of the lysimeters.

Fig. 3 Weighing of lysimeters by portable scales moving on tracks.

Fig. 4
View of lysimeters from the underground tunnel. At the left a window, at the right the resistance thermometers, at the bottom drainage arrangements.

A rain gage of the size of 1 sqm. is operating during the vegetation period; its surface is equal to that of the surface of the lysimeter and its level is that of the surrounding soil. The weight of the lysimeter is daily controlled by a movable scale with a tolerance of a 0.1 mm water column (see fig. 3). The individual lysimeters can be reached from an underground tunnel.

Meteorological equipment

1 mercury thermometer 2 mts above ground level
1 psychrometer 2 mts above ground level
1 thermograph 2 mts above ground level
1 hygrograph 2 mts above ground level
1 maximum thermometer 2 mts above ground level
1 minimum thermometer 2 mts above ground level
1 mercury thermometer 1 m above ground level
1 thermohygrograph 1 m above ground level
6 mercury thermometers at 1, 5, 15, 30, 50, 100 cms below ground level
8 resistance thermometers at 1, 5, 15, 30, 50, 100, 140 and 200 cms below ground level
36 resistance thermometers at 1, 5, 15, 30, 50, and 100 cms in the lysimeters (with recorder)
1 rain gage 500 sq.cms for use in mountainous areas, 1 m above ground level
1 rain recorder 200 sq.cms 1 m above ground level
1 rain gage 10,000 sq.cms at soil surface
1 snow board
3 evaporation meters according to Ramsauer at ground level and at 1 and 2 mts above ground level
1 evaporation recorder according to Ramsauer 1 m above ground level
1 sunshine autograph
1 star pyranometer for measuring radiation (for certain periods)
1 actinograph (for a certain period only)
1 wind vane
1 wind velocity recorder 1 m above ground level
20 soil moisture meters (modified plaster of Paris blocks)

Soil

All lysimeters are containing colluvial brown soil of local origin. For results of physical and chemical tests see table 6. This is a very uniform loamy soil which is excellently suitable for agricultural purposes. Its great water storing capacity and its permeability are emphasized. The gradual increase of its content in clay and iron compounds up to the depth of 230 cms is the outward sign of a considerable shifting of soil materials and temporary percolation.

Percolation

Conclusions can be drawn from the average total quantities in lysimeters I, II and III percolated during the period 1953/58, regarding the water consumption in spring and summer, and storage in the autumn and winter. If thaw sets in there are deviations in percolation due to the different magnitude of the snow cover and the uncontrolled surface runoff. A further reason for deviation may be that the size of cracks in the monoliths near the walls diminished in the order in which they had been extracted from the soil, i. e. II, I, III. From April onward consumption by plants and evapo-

TABLE 6

Soil analysis "Petzenkirchen — Pflanzenschutzgarten", Lysimeter
Colluvial Brown Earth

Horizon	Depth cms	Soils	Size of Particles mms: > 2.0	2.0—0.2	0.2—0.02	0.02—0.002	< 0.002	Pore Space Distribution mms: < 0.003	0.003—0.03	[illegible]
			Weight — %					Volume — %		
A	0—30	gray ocre colored loam		4	59	34	3	10.8	27.4	1[illegible]
B_1	30—100	ocre colored loam		5	54	33	8	12.5	20.7	5[illegible]
B_2	100—170	ocre colored rust granular loam		1	50	35	14	15.9	17.6	5[illegible]
B_2/G_1	170—230	ocre colored, light gray and rust spotted loam		0	51	36	13			
G_2/C	230—330	ocre colored, light gray spotted, fine sandy loam		0	65	28	7			
G_3/D_1	330—650	ocre colored, light gray spotted loam		1	59	33	7			
G_4/D_1	650—760	ocre colored, dark brown spotted loam		3	62	27	8			
G_5/D_2	760—(800)	ocre colored, dark brown spotted, gritty fine sandy loam	24	4	63	25	8			

ration are clearly effective and then, from June to November, there is no percolation at all, except during heavy rainfalls. This phenomenon shows that, in summer and autumn, no important increase in the volume of the ground water in the colluvial brown soil in Petzenkirchen may be expected.

Maximum percolation takes place during the month of March. There is no percolation at all from September to November. In autumn the lack of soil moisture is so great that the precipitation of three months is needed to catch up with the field capacity.

At an average precipitation of 500 mms during the vegetation period percolation amounted to no more than 10 per cent, while it was above 34 to 47 per cent during the rest of the year.

Pore Space	Permeability ms/day	Liquid Limit	Plastic Limit	Plasticity Index	Hygroscopicity 10 % H_2SO_4	Solid particle Density	Bulk Density	pH	Carbonates	Organic Matter	Real Humic Matter	Fe_2O_3
									Weight — %			
8.3	4.6	35.5	23.2	12.3	3.93	2.66	1.37	8.2	trace	3.4	2.2	2.0
9.1	1.0	30.1	18.6	11.5	3.78	2.71	1.65	7.8	0		1.0	2.1
9.1	1.6	33.7	18.7	15.0	4.86	2.69	1.64	7.3	0			2.3
		38.8	21.0	17.8	6.64			7.2	0			3.2
		29.0	21.4	7.6	3.19			8.0	10.9			2.6
		31.7	21.7	10.0	4.08			7.5	0			3.3
		33.9	21.1	12.8	5.10			7.4	trace			4.2
		32.0	20.7	11.3	4.94			7.6	trace			3.9

Evaporation

As the evaporation value proves to be the effective result of various influences the action of which is constantly changing, weighable lysimeters are excellent measuring instruments for potential evaporation. However, as lysimeters are costly installations, an effort had to be made to discover the exact relation between evaporation, measured by the evaporator according to Ramsauer, and evapotranspiration in lysimeters.

Concerning evaporation values it may be said that because of disturbances in weighing processes in winter (snow), values given are exclusively those referring to the growing season from April to September.

TABLE 7

Average precipitation and percolation at Lysimeters I, II and III 1953/1958 in mms

		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year	IV–IX	I–III, X–XII
Precipitation		36	53	32	59	79	114	113	85	49	55	35	45	755	499	256
Percolation of Lysimeters	I	16	38	26	21	13	6	4	5	.	.	.	9	138	49	89
	II	23	45	31	19	16	6	2	6	.	.	.	20	168	49	119
	III	18	39	27	20	13	5	.	6	.	.	.	4	132	44	88

From coefficients of percolation of Table 8 the relation between percolation, precipitation and time of the year can be clearly observed.

TABLE 8

Coefficients of percolation during the period 1953/1958 in mms

Lysimeter	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
I	0.44	0.72	0.81	0.36	0.16	0.05	0.04	0.06	.	.	.	0.20	0.18
II	0.64	0.85	0.97	0.32	0.20	0.05	0.02	0.07	.	.	.	0.45	0.22
III	0.50	0.74	0.84	0.34	0.16	0.04	.	0.07	.	.	.	0.09	0.17

	IV-IX	I-III, X-XII
Lysimeter I	0.10	0.35
Lysimeter II	0.10	0.47
Lysimeter III	0.09	0.34

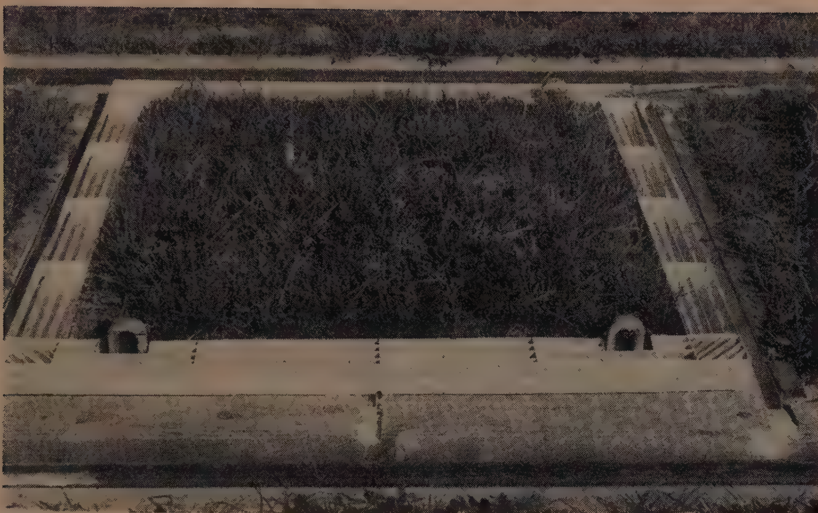

Fig. 5 “Splash screen” surrounding the lysimeters.

TABLE 9

Lysimeter-evapotranspiration in mms

Year	Lysi-meter	IV	V	VI	VII	VIII	IX	Vegetation-period
1953	I	18	68	147	163	109	58	563
	II	17	67	147	160	112	59	562
	III	17	73	149	170	113	60	582
1954	I	38	133	90	117	114	43	535
	II	35	128	92	99	93	54	501
	III	31	144	93	118	127	48	561
1955	I	31	86	97	107	93	74	488
	II	34	96	98	112	92	75	507
	III	38	97	100	111	92	74	512
1956	I	58	132	89	176	149	67	671
	II	66	125	84	170	135	61	641
	III	55	125	87	172	145	69	653
1957	I	64	128	117	154	129	63	655
	II	58	105	108	150	133	50	604
	III	54	108	111	166	145	50	634
1958	I	45	172	129	130	115	59	650
	II	53	158	132	126	118	61	648
	III	49	169	139	123	116	61	657

average of lysimeter		I	594	
1953-1958	„	II	577	590
	„	III	600	

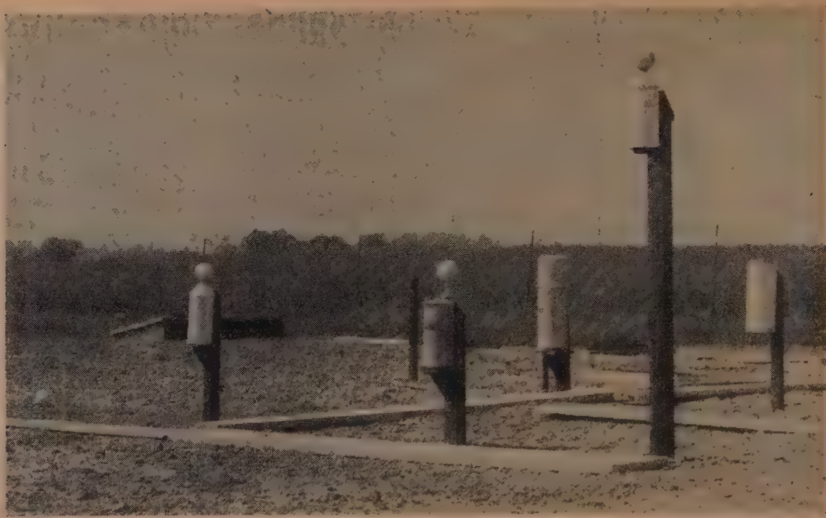

Fig. 6 Evaporation meter, evaporation recorder and rain recorder at ground level and 1 and 2 mts above ground level.

Correlation of ball evaporation—lysimeter-evaporation

Results of measurements carried out during the period 1953/58 with the Ramsauer evaporator at 2 mts above ground level were used for correlation of ball evaporation to lysimeter evapotranspiration. Evaporation measured by the Ramsauer evaporator will be referred to in the following as ball evaporation because of the spherical shape of the evaporation body of this instrument.

Because of the sensibility to frost of the Ramsauer evaporation meter (7) the only measurement results which could be used were those of May to October. Comparison of results calculated for the entire vegetation period and for individual months, showed a bad degree of correlation, whereas correlation was much better if calculations were carried out on the basis of the periods of development of the grass cover, the duration of which can be seen from the following table. First of all an examination was made of all relations between evapotranspiration and ball evaporation on the one hand, and meteorological elements, such as duration of sunshine, global radiation, saturation deficit, during the 4 development periods a-d, on the other. Results are given in Table 10, in regression equations and correlation coefficients of evapotranspiration, ball evaporation and the above mentioned meteorological elements.

Period of development	beginning with	ending with
a	sprouting	10 cms high
b	10 cms high	harvest
c	after the harvest	10 cms new growth
d	after the vegetation period	

Period	beginning with	ending with
a	sprouting	10 cms high
b	10 cms high	harvest
c	after the harvest	10 cms new growth
d	after the vegetation period	

It can be seen that correlation is best during the period of development (b), i. e. from the time when the grass is 10 cms high until the harvest.

An ideal relation of lysimeter-evapotranspiration and ball evaporation has been calculated in order to cut out the influence of systematic errors. This could be successfully done in view of relations of the duration of sunshine on the one hand to lysimeter-evapotranspiration, and on the other

TABLE 10

Regression equations and coefficients of correlation between lysimeter evapotranspiration (y), ball evaporation (x) and various meteorological elements (s, g, d) influencing evaporation. 1953-1956.

	PERIOD OF DEVELOPMENT a		PERIOD OF DEVELOPMENT b	
	lysimeter (y) mms	ball (x) mms	lysimeter (y) mms	ball (x) mms
Duration of sunshine hrs (s)	$y = 2.408 \cdot 1.049^{s}$ $r = 0.47$	$x = 1.44 + 0.21 \cdot s$ $r = 0.63$	$y = 2.23 \cdot 1.095^{s}$ $r = 0.83$	$x = 1.59 + 0.324 \cdot s$ $r = 0.87$
Global radiation cal/cm² (g)	$y = 2.84 + 0.005 \cdot g$ $r = 0.53$	$x = 0.307 + 0.0054 \cdot g$ $r = 0.68$	$y = 0.57 + 0.0103 \cdot g$ $r = 0.88$	$x = 0.23 + 0.0079 \cdot g$ $r = 0.85$
Saturation deficit 14 hour mms (d)	$y = 1.91 \cdot d^{0.233}$ $r = 0.38$	$x = 0.96 \cdot d^{0.625}$ $r = 0.75$	$y = 2.26 \cdot d^{0.469}$ $r = 0.75$	$x = 1.675 \cdot d^{1.064}$ $r = 0.85$
Evaporation of ball 2 mts ab. ground lev. (x)	$y = 1.595 \cdot 1.176^{x}$ $r = 0.40$	——	$y = 1.849 \cdot 1.274^{x}$ $r = 0.80$	——
	PERIOD OF DEVELOPMENT c		PERIOD OF DEVELOPMENT d	
Duration of sunshine hrs (s)	$y = 1.614 \cdot 1.072^{s}$ $r = 0.52$	$x = 1.59 + 0.264 \cdot s$ $r = 0.82$	$y = 1.174 \cdot 1.094^{s}$ $r = 0.51$	$x = 0.88 + 0.28 \cdot s$ $r = 0.81$
Global radiation cal/cm² (g)	$y = 0.21 + 0.0059 \cdot g$ $r = 0.71$	$x = -0.05 + 0.0079 \cdot g$ $r = 0.91$	$y = 0.43 + 0.05 \cdot g$ $r = 0.67$	$x = 0.31 + 0.008 \cdot g$ $r = 0.75$
Saturation deficit 14 hour mms (d)	$y = 1.51 \cdot d^{0.33}$ $r = 0.52$	$x = 1.04 \cdot d^{0.624}$ $r = 0.77$	$y = 0.783 \cdot d^{0.366}$ $r = 0.51$	$x = 0.79 \cdot d^{0.518}$ $r = 0.64$
Evaporation of ball 2 mts ab. ground lev. (x)	$y = 1.479 \cdot 1.18^{x}$ $r = 0.39$	——	$y = 0.761 \cdot 1.288^{x}$ $r = 0.55$	——

to ball evaporation. The following regression equations were found for the 4 periods of development, in which

y = lysimeter evapotranspiration and
x = ball evaporation

a : sprouting to 10 cms	. . . .	$y = 0.792 \cdot 1.503^x$
b : 10 cms to harvest	. . . .	$y = 1.261 \cdot 1.362^x$
c : after the harvest to 10 cms	. . . .	$y = 0.268 \cdot 1.957^x$
d : after the vegetation period (Sept., October)	. . . . . .	$y = 1.036 \cdot 1.052^x$

Fig. 7 which shows the regression equation curves, curve d stands for the diminuation of the lysimeter evapotranspiration caused by the termination of the vegetation period.

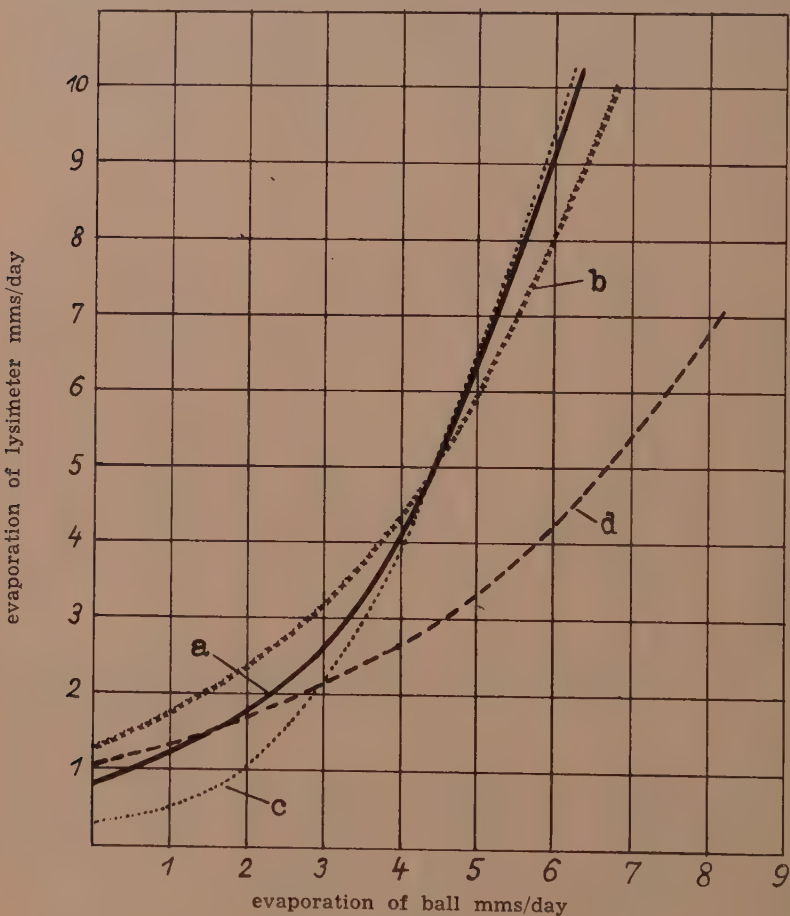

Fig. 7

Regression curves for periods of development a, b, c, d

Losses through leaching

In collaboration with the Agricultural Chemical Federal Experimental Station in Linz a determination of losses in nutrients caused by percolation at a depth of 1.30 mts was made, more especially of losses of K_2O under climatic conditions reigning in the pre-Alpine district. In March 1950, lysimeter II was therefore fertilized at the rate of 600 kgs/ha, 50 per cent K_2SO_4.

Up to March 1956, 249 liters of water percolated in lysimeter I which had not been fertilized, and 257 liters in lysimeter II, while total precipitation amounted to 798 mms. Practically no potash was leached out, but more calcium and magnesia was lost by seepage in lysimeter I because of the ionic exchange. Too little attention has so far been given to this reaction of the soils. According to results achieved, maintenance liming should amount to at least 190 kgs/ha of calcium oxyde per annum.

TABLE 11

Losses in nutrients by leaching

Losses in nutrients	Lysimeter I (kg/ha)	Lysimeter II (kg/ha)
anorganic compounds:	288.7	352.3
thereof CaO	117.8	151.3
MgO	33.3	49.9
K_2O	0.9	1.1

Heat economy

Within the framework of this publication it may be mentioned that the soil of the lysimeters was on the average by 0.5 centigrades warmer than the surrounding soil. During the period 1954/58 average annual values of temperature at individual depths amounted to:

depth	average annual temperature 1954/58
1 cm	8.7
5 cms	8.5
15 cms	8.2
30 cms	8.6
50 cms	9.0
100 cms	8.4

VI. Lysimeter Experiments in Ober Siebenbrunn

Within the framework of an irrigation project carried out in the Marchfeld, which is a large plain of average low rainfall to the east of Vienna, and is an excellent agricultural district, a lysimeter station was set up in Ober Siebenbrunn in 1957. This station serves the collection of experience

regarding losses by percolation and the water economy of various types of soils in the Marchfeld.

The station consists of 6 square funnel-lysimeters (Ebermayer) of a surface of 0.05 sq. mts, arranged at a depth of 25, 50 and 75 cms. Three funnel lysimeters are measuring the percolation water under grass cover, three that of fallow soils. In addition to these lysimeters four monolith lysimeters in steel boxes (0.5 x 0.5 x 0.75 m) were also installed. They are not weighable and are supposed to provide information regarding the water cycle in the following soil types: riverside soil, wind blown soil, and chernozem soil.

These observations have not yet been carried out long enough to allow for a report of results.

It is with great pleasure that I am acknowledging the great help which all my colleagues in the Federal Institute for Agricultural Engineering and Soil Science, and more especially F. Feichtinger (correlations) and F. Blümel (results of soil analyses) have given me.

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EVAPORATION ET ECOULEMENT EN CASES LYSIMETRIQUES, AU CHAMP, ET DANS LES BASSINS DE COURS D'EAU

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RÉSUMÉ.

I — Evaporation et écoulement en cases lysimétriques et dans le milieu naturel ou au champ, contrôle des cases lysimétriques.

Par leur principe même le lysimètre entonnoir et la case lysimétrique modifient la circulation de l'eau dans le sol ; on ne recueille d'eau au drain que si elle franchit la limite sol/air. Ce défaut rend le lysimètre entonnoir inutilisable, par contre son incidence sur le bilan hydrique des cases lysimétriques est souvent faible. Une installation de cases lysimétriques convenablement mises en place et contrôlées peut donc apporter une contribution valable à l'étude des bilans hydriques naturels. Quelques indications sont données pour la mise en place et le contrôle.

II — Cases lysimétriques et bassins de cours d'eau : comparaison des bilans hydriques.

Les hauteurs d'eau évaporées dans les bassins de cours d'eau des différentes régions du monde varient surtout en fonction du climat ; sous certaines conditions, il en est de même pour les cases cultivées, cases et bassins donnent des évaporations voisines lorsqu'ils sont situés sous le même climat ; l'étude des bilans naturels aide alors à contrôler les cases lysimétriques, les résultats des mesures lysimétriques permettent d'analyser l'écoulement des cours d'eau.

I — Evaporation et Écoulement en Cases lysimétriques et dans le Milieu naturel ou au Champ, Contrôle des Cases lysimétriques.

Dans une case lysimétrique on s'efforce de reproduire pour le mieux les conditions d'un certain milieu naturel, tout en se ménageant la possibilité de recueillir quantitativement les eaux de drainage ; la mesure du drainage et des précipitations permet d'évaluer l'évaporation pour des intervalles de temps convenablement choisis (précaution inutile lorsque les cases sont pesables).

Ces évaluations en case lysimétrique constituent-elles des approximations suffisantes pour les grandeurs du drainage et de l'évaporation dans le milieu naturel ? Les causes d'écarts peuvent être classées en deux groupes :

— celles provenant du principe des lysimètres

— celles provenant de leur réalisation et de leur utilisation.

La présente note apporte des éléments à la discussion de quelques erreurs.

Effet du fond drainant : A priori les plus graves erreurs de principe devraient être celles qui proviennent de l'interruption du système des forces capillaires dans le sol par le fond drainant.

Dans les « lysimètres entonnoirs » ou « lysimètres D'EBERMEYER », cet inconvénient est poussé au maximum, si bien qu'il rend ces appareils inutilisables. Le fait qu'ils recueillent très peu d'eau avait été invoqué pour étayer l'hypothèse selon laquelle les précipitations n'alimentent pas de façon notable

les réserves en eau du sous-sol. En réalité, comme DIENERT (1) l'a montré, l'eau contourne ces appareils ; DIENERT les a modifiés par adjonction de parois latérales verticales, il a ainsi provoqué l'établissement d'une charge d'eau capable de vaincre la barrière capillaire, et recueilli des quantités d'eau qui peuvent atteindre 29 % des précipitations annuelles à Auxerre ; le « pluviomètre souterrain » de DIENERT se rapproche plus de la véritable case lysimétrique que du lysimètre entonnoir.

Le lysimètre entonnoir étant éliminé au profit de la case lysimétrique proprement dite, si l'objection envisagée (interruption du système capillaire par le fond drainant) est moins grave pour celle-ci, elle subsiste néanmoins. La charge d'eau nécessaire pour que le drainage apparaisse ne se produit pas dans la nature lorsque le sol est perméable et pourvu d'un bon drainage naturel ; il existe donc en ce cas pendant les périodes de drainage et aux alentours de celles-ci un excès d'humidité au fond des cases ; certains auteurs (2,3) ont montré la possibilité d'obtenir dans ce cas des conditions d'humidité plus proches des conditions naturelles en exerçant une succion à travers le fond drainant ; cette succion doit être d'autant plus forte que la granulométrie du sol est plus fine, puisqu'elle remplace la succion capillaire des couches du sous-sol qui manquent dans la case lysimétrique ; il semble que l'évaluation de la succion à appliquer et l'application de cette succion se heurtent à des difficultés.

En réalité, la perturbation due au fond drainant entraine-t-elle nécessairement des différences graves entre les grandeurs de l'évaporation et de l'écoulement en cases et leurs grandeurs au champ ? Il ne semble pas qu'il en soit ainsi. WALLIHAN précise que dans la mesure où le drainage naturel est gêné par des couches imperméables les conditions dans les cases lysimétriques peuvent se rapprocher des conditions naturelles. YANKOVITCH et ses collaborateurs (4) ont utilisé à Tunis des cases lysimétriques doublées de « cases de végétation » qui n'ont pas de fond drainant, or les masses des récoltes sont généralement voisines pour les deux types de cases, et si dans quelques cas les cases lysimétriques donnent des récoltes systématiquement supérieures aux « cases de végétation », c'est l'inverse pour d'autres cas ; ces chercheurs ont remarqué que les profils hydriques, qui semblent souvent peu différents, peuvent présenter dans les couches profondes un excès d'humidité pour les cases lysimétriques en période de drainage, et par contre en période sèche une humidité plus faible que pour les cases sans fond (circulation per ascensum). A Rothamsted fonctionnent depuis 88 ans trois cases nues ; elles drainent des quantités d'eau à peu près égale bien que leurs profondeurs soient différentes : respectivement 50, 100 et 150 cm.

Enfin, comme nous le verrons plus loin, la comparaison des cases lysimétriques avec les bassins de cours d'eau montre qu'au moins en ce qui concerne les grandeurs annuelles moyennes de l'évaporation et de l'écoulement, les désaccords entre les cases lysimétriques et le milieu naturel sont généralement trop faibles pour que nous puissions les mettre en évidence ; ceci minimise toutes les objections qui peuvent être faites à ce sujet contre l'emploi de cases lysimétriques.

Installation et contrôle des cases lysimétriques : On vient de voir que les reproches qui peuvent être faits a priori aux cases lysimétriques n'interdisent nullement leur utilisation pour évaluer les grandeurs de l'évaporation et de l'écoulement dans le milieu naturel. Par contre, lorsqu'on installe puis utilise des cases lysimétriques, des précautions doivent être prises pour leur assurer un fonctionnement satisfaisant et pour contrôler ce fonctionnement. Nous ne rappellerons pas toutes les conditions relatives à une construction

soignée : absence de fuites au fond des cases, de gouttières sur les bords, etc... ; précisons seulement quelques points :

— Surface supérieure des cases : on obtient en sol nu pour Versailles (anciennes cases) et Groningen des résultats mensuels moins reproductibles que pour Rothamsted, cela peut être dû en partie aux différences de dimensions car les cases de Rothamsted ont une surface de 4 m², contre 1 m² à Versailles et à Groningen ; il semble que la surface supérieure de la case doit être au minimum un cercle ou un carré de 1 m² ; dans les régions à pluies violentes et pour les sols sujets à d'importants retraits il est préférable d'aller jusqu'à 4 m² pour diminuer les effets de parois (Tunis, Pusa).

— Profondeur des cases : on limitera les inconvénients dus au fond drainant en utilisant des cases suffisamment profondes (1 m et plus), afin d'éloigner de la surface la zone où l'humidité est perturbée.

— Mise en place de la terre : on a parfois insisté sur les remaniements infligés au sol et sur les conséquences imprévisibles que cela pouvait avoir pour le drainage ; ces effets sont souvent faibles comme le montre la comparaison entre des cases construites de façons différentes : cases bâties autour du sol en place, cases emplies d'un matériau homogène, cases dans lesquelles on a apporté les différents horizons d'un sol afin de reconstituer le profil initial (5 p. 99, A. A. 1955 p. 49). Rappelons aussi que dans les anciennes cases de Versailles le sol a repris en 2 ans sa densité apparente initiale (6).

On peut donc réussir à obtenir un remplissage convenable des cases, au moins lorsque le matériau est meuble. Il n'en est pas moins recommandable d'employer une méthode qui réalise rapidement un tassement proche de ce qui se produit dans la nature ; ainsi les nouvelles cases de Versailles ont été emplies de la façon suivante selon les indications de S. HENIN :

Laisser sécher le matériau à l'air ; ceci fait, apporter sur le fond drainant de la case alternativement de l'eau et de la terre sèche, le niveau de l'eau restant toujours supérieur à celui de la terre mais sans excès (disons moins de 20 cm) ; la terre sèche tombe dans cette faible couche d'eau qui la recouvre entièrement, et y éclate ; lorsque la case est pleine, on ouvre la goulotte de drainage et laisse ressuyer. Cette méthode a priori séduisante a donné de bons résultats non seulement pour le limon de Versailles mais aussi pour des terres de Limagne difficiles à travailler.

— Neige : pour les précipitations se produisant sous forme de neige, le bilan est difficile à faire à moins qu'on ne dispose de cases géantes Castricum) ; la neige peut être accumulée par le vent sur une case ou au contraire en être balayée, ainsi les mesures au nivomètre ne permettent pas d'évaluer les quantités de neige effectivement apportées à une case, celles qui ont fondu sur cette case.

— Contrôle du fonctionnement : il est bon qu'une station lysimétrique possède plusieurs cases de chacun des types qu'elle emploie ; ces cases seront identiques quant aux dimensions, au mode de construction et de remplissage, à la nature du sol, et aux cultures ; on peut admettre des différences sur les fumures et amendements ; ces cases se contrôlent les unes les autres, des écarts importants entre leurs drainages sont la preuve d'un fonctionnement défectueux (à moins qu'ils ne soient explicables par de grandes différences dans le développement de la végétation).

Exemples : à Rothamsted dans des périodes de 6 ans allant de 1871 à 1933, les évaporations des cases de 50 cm et 1 m oscillent entre 90 % et 105 % de celle de la case de 1 m,50. A Groningen, bien que les cases reçoivent des fumures différentes, et que la masse des récoltes diffère d'une case à l'autre, leurs drainages (qui ne représentent en moyenne qu'environ 30 % des pré-

cipitations) diffèrent assez peu : si chaque année on évalue le drainage de chaque case en % de la moyenne des 8 cases on constate que la plupart des résultats oscillent entre 90 et 110. Entre les anciennes cases de Versailles (3 nues comparables et 2 cultivées) les accords ont été généralement satisfaisants (écarts annuels entre les drainages de l'ordre de 1/20e des précipitations) ; avec les nouvelles qui sont plus grandes (2 m²) les écarts sont nettement plus faibles.

Après la mise en place d'une installation de cases lysimétriques, une fois les 3 à 5 premières années écoulées, les valeurs annuelles de l'évaporation (précipitations moins drainage) varient peu sous la plupart des climats, ou du moins si on considère des groupes d'années successives tels que les précipitations annuelles moyennes soient voisines, les évaporations annuelles moyennes doivent être voisines. On peut ainsi comparer une case à elle-même pour la contrôler, des écarts importants font soupçonner un fonctionnement peu fidèle.

Rappelons qu'à Tunis un contrôle intéressant des cases lysimétriques est assuré par des cases sans fond, donc plus proches des conditions au champ, les comparaisons entre les deux types portent sur les profils hydriques et sur les récoltes.

Les rivières fournissent aussi un élément de contrôle pour les cases cultivées : si dans les cases le développement de la végétation, les conditions d'enracinement, et la nature du sol, ne diffèrent pas extrêmement des conditions moyennes dans la région, l'écoulement annuel moyen doit être du même ordre que celui des bassins de cours d'eau (écarts généralement inférieurs à 50 mm par an, dépassant très rarement 100 mm) ; si les écarts sont élevés, il faut rechercher pourquoi car un mauvais fonctionnement des cases (fuites, sol gâché, ...) est à craindre.

Conclusion : Une installation de cases lysimétriques mise en place et conduite avec les précautions indiquées doit donc donner des résultats valables ; comme certaines conditions des terres cultivées sont reproduites en cases plus aisément que celles de milieux plus naturels, on peut obtenir ainsi une contribution particulièrement utile pour l'étude des bilans hydriques de ces terres.

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II — Cases lysimétriques et Bassins de Cours d'eau : Comparaison des Bilans hydriques.

Rappel des formules :

Le bilan de l'eau dans la nature et au champ est encore connu de façon fragmentaire ; c'est afin de relier les informations dont nous disposons et d'en généraliser l'emploi qu'on a mis au point (1, 2, 3) des formules simples qui permettent d'évaluer l'évaporation en fonction des grandeurs météoriques les mieux connues : précipitations et température, et parfois d'autres données dont la connaissance précise est relativement accessoire (1).

Si les quantités d'eau sont rapportées à la surface du bassin et évaluées en mm de hauteur d'eau liquide, le bilan annuel moyen du bassin d'un cours d'eau peut généralement s'écrire : D $=$ P — E ; D mesure l'écoulement, P les précipitations, E l'évaporation (valeurs annuelles moyennes). On a montré que E peut être évalué par la formule :

$$\text{(I)}\quad E = \frac{P}{\sqrt{0{,}9 + \dfrac{P^2}{L^2}}}$$

L étant une fonction de t, température annuelle moyenne de l'air.

Pour 254 bassins situés principalement en Europe, en Afrique, en Amérique, on obtient ainsi en fonction de P et de t des valeurs de E, et de D $=$ P — E, dont les différences avec les valeurs mesurées sont inférieures à 40 mm dans 53 % des cas, et au $1/5^e$ de D dans les $2/3$ des cas.

Les plus grands écarts entre valeurs observées et calculées proviennent du fait que le calcul fait intervenir uniquement les valeurs annuelles moyennes de P et t, sans tenir compte de la répartition des précipitations et de la variation de température au cours de l'année. Cette insuffisance est évitée dans l'étude des cases lysimétriques qui permettent d'évaluer certains bilans mensuels et même décadaires. On a montré qu'ici l'évaporation peut être calculée approximativement par les formules :

$$\text{(II)}\quad E = \frac{P + a}{\sqrt{1 + \left(\dfrac{P + a}{l}\right)^2}}$$ lorsque le sol est nu

et $$\text{(III)}\quad E = \frac{P + a + V}{\sqrt{1 + \left(\dfrac{P + a}{l} + \dfrac{V}{l}\right)^2}}$$ lorsqu'il porte une végétation active (pour V $=$ o on retrouve la formule précédente)

on n'utilise plus ici des valeurs annuelles moyennes mais des valeurs décadaires ; l fait intervenir en plus de la température la radiation globale ; enfin V est calculé en fonction de la masse de matière végétale formée, en réalité il représente non seulement l'activité de la végétation mais aussi le système racine-sol qui en est corrélatif et qui est souvent mal connu.

A partir des valeurs de l'évaporation on calcule selon le cas l'assèchement ou l'écoulement. Ces formules, ajustées pour Versailles, Groningen, Rothamsted, ont été appliquées à des stations situées en Afrique du Nord,

(1) Nous n'exposons pas ici le détail des méthodes de calcul ; se reporter aux références 2 et 3.

TABLEAU 1

	L (en mm)	$\Sigma\, l$ (en mm)
Craibstone	500	297
Rothamsted	570	388
Groningen	585	430
Versailles	610	487
Toulouse	775	624
Tunis	1.000	855
Pusa	1.660	1.289
Buitenzorg	1.710	1.260

en Inde, etc.... ; entre les écoulements annuels calculés (somme de 36 écoulements décadaires) et les écoulements observés, l'écart absolu est inférieur à 40 mm plus de 2 années sur 3, et l'écart relatif est inférieur à $^1/_5$e avec la même fréquence.

Remarquons tout de suite que dans la formule (II) le terme l joue un rôle analogue à celui de L dans la formule (I) ; L représente le facteur thermique, l le facteur héliothermique de l'évaporation, l'autre facteur de l'évaporation étant l'eau disponible : P ou P + a ; L est une évaluation de l'évaporation annuelle maximum qui peut être atteinte si les précipitations sont abondantes, l a le même sens pour une décade en sol nu. Calculons donc les sommes des l décadaires d'une année pour quelques stations et comparons les aux L calculés en fonction des températures annuelles moyennes de ces stations:

On constate que les deux grandeurs sont fortement corrélatives et assez proches l'une de l'autre, $\Sigma\iota$ étant de l'ordre des $^3/_4$ de L ; comme l est relatif au sol nu et L au sol couvert de sa végétation naturelle ou cultivée, il est normal que $\Sigma\iota$ soit inférieur à L.

Comparaison des bilans hydriques : (référence 2 p. 109 ou A. A. 1955 p. 58)

Cette comparaison porte sur les bilans hydriques des cases lysimétriques et des bassins de cours d'eau, c'est-à-dire de systèmes qui diffèrent :

— par leur origine : expérimentale pour les cases, naturelle pour les bassins

— par leur surface, de l'ordre du m² pour les cases, du km² et bien plus pour les bassins

— par le domaine de circulation souterraine de l'eau, concernant seulement le sol et interrompue par le fond drainant dans les cases, intéressant aussi les réserves du sous-sol dans les bassins.

Malgré ces différences, le tableau 1 fait prévoir un certain accord entre les valeurs des évaporations. Les possibilités de comparaison directe sont faibles car il est rare que sur un bassin se trouve une installation de cases lysimétriques placées dans une station dont les conditions climatiques soient proches des conditions moyennes du bassin ; c'est donc surtout par l'intermédiaire des formules citées plus haut que nous avons pu faire ces comparaisons : comparaison entre les évaporations (et drainages) observées en cases lysimétriques et les évaporations calculées par la formule (I) qui se produiraient sur des bassins qui seraient situés sous le même climat ; comparaison entre les évaporations observées sur les bassins naturels et les évaporations calculées par la formule (III) qui se produiraient sur des cases qui seraient situées sous les mêmes climats.

Au moyen de la formule (I), on peut évaluer l'évaporation et le drainage en portant dans cette formule les valeurs de P et t mesurées à la station où se trouvent les cases lysimétriques (il peut être préférable d'utiliser (I) pour évaluer à partir des bilans connus des bassins de la région celui d'un bassin qui aurait lesdites valeurs P et t).

Le tableau 2 indique pour 7 stations possédant des cases lysimétriques cultivées les valeurs annuelles moyennes suivantes :

température de l'air, P, D mesuré, éventuellement D mesuré en sol nú avec les mêmes précipitations, D calculé par décade au moyen de la formule (III) (sol cultivé), D calculé avec la formule (I) des rivières, ainsi que la masse moyenne de la matière sèche récoltée par an en q/ha.

On constate que pour 4 stations sur 7 la formule des rivières donne une évaluation acceptable du drainage des cases cultivées : écarts inférieurs à 20 % dont 3 écarts inférieurs à 10 %. Pour Groningen l'accord est moins bon mais cette station se distingue par ses très fortes récoltes, ceci explique probablement que l'évaporation soit supérieure à ce qu'elle serait en moyenne sur le bassin d'un cours d'eau. Tunis et Pusa enfin sont des stations pour lesquelles les précipitations sont concentrées sur quelques mois de l'année d'où les écarts avec la formule (I) qui ne tient pas compte de ce facteur. Considérant les évaporations on constate que pour 6 stations les valeurs mesurées (cases) sont comprises entre 386 et 524 mm par an, les valeurs calculées (rivières) entre 434 et 504, et pour Pusa l'évaporation mesurée est de 839 mm, l'évaporation calculée de 990 mm.

Réciproquement nous avons essayé l'emploi de la formule (III), qui se réduit à (II) lorsque la végétation n'est pas active, pour calculer le bilan des bassins de cours d'eau. Le tableau 3 donne 8 exemples portant sur des régions à climats très différents, chauds ou froids, arides ou humides, avec des précipitations soit réparties assez uniformément sur toute l'année, soit surtout abondantes en saison froide : Algérie, ou en saison chaude : Ukraine, Dakota du Nord.

Ce tableau permet de comparer pour chaque bassin les valeurs annuelles moyennes (en mm de hauteur d'eau) de l'écoulement mesuré par jaugeage

TABLEAU 2

Stations où sont situées les cases	t °C	Pmm	Drainages annuels moyens, en mm				Récolte m. sèche en q/ha/an
			Dmes. sol cultivé	Dmes. sol nu	Dcalc. form. (III)	Dcalc. form. (I) (rivières)	
Versailles . . .	10,3	594	143	(230)	152	157	51
Groningen . . .	9,6	709	185	(400)	212	250	109
Craibstone . . .	7,35	829	433		460	395	41
Harrogate . . .	8,2	779	393		343	330	
Toulouse . . .	13,8	540	86		96	82	
Tunis	17,5	551	104 (blé ap. blé)	(233)	78,5	47	61
Pusa	24,6	1.180	341 (nu en saison sèche)	(465)	446	190	78

TABLEAU 3

Rivières	Pmm	Dmes.	Dcalc. (I)	Dcalc. (II) (form. des cases nues)	Dcalc. (III) (form. des cases cultivées)	Dcalc. (III) avec 200 q/ha au lieu de 50
Red River (Dak. N.) .	532	32	196	203	47	
Mina (Alg.)	475,5	53	35	106	34	
Dniestr	548	107	174	207	94	
Seine (à Paris) . . .	715	231	247	314	172	
Suède (S., z. II) . . .	649	289	259	356	244	
O. Djen Djen (Alg.) . .	1300	611	582	845	732	
Tji Kapundung (Java) .	2650	1580	1675	1864	1640	1507
Tji Anten (Java) . . .	4935	3747	3690	3933	3815	3745

du cours d'eau : Dmes., et de l'écoulement calculé avec la formule des cases cultivées : Dcalc. (III) ; on a porté aussi sur le tableau les précipitations : P, l'écoulement calculé avec la formule des cases nues : Dcalc. (II), et avec celle des rivières : Dcalc. (I).

Les évaporations sûr ces bassins sont échelonnées entre 360 et 1188 mm/an ; la formule (III), établie pour les cases, les évalue avec des écarts relatifs de l'ordre de $^1/_{10}$.

On remarquera que la formule établie pour les cases peut donner une meilleure évaluation du bilan des rivières que la formule établie pour les rivières : c'est le cas pour la Red River (N. D.), car la formule (III) n'a pas comme (I) le défaut de ne pas tenir compte des variations de P et t au cours de l'année.

La formule (III) fait intervenir un terme V (= « végétation »), fonction de la quantité de matière végétale formée annuellement ; pour raison de simplicité et pour éviter un choix plus ou moins arbitraire nous avons pris partout 5 tonnes de matière sèche par ha/an ; pour les 2 rivières de Java nous avons également fait le calcul avec 20 tonnes, ce qui est certainement plus proche de la réalité ; les résultats montrent que même lorsque cette grandeur est mal connue on obtient des ordres de grandeur intéressants pour les évaporations et écoulements.

Enfin nous avons pu faire quelques comparaisons directes entre le bilan annuel moyen des rivières et celui des cases cultivées ; ces comparaisons confirment l'accord mis en évidence par l'intermédiaire des formules :

pour 3 cours d'eau du bassin de la Seine ayant P inférieur à 650 mm par an, la moyenne des 3 valeurs de P est 600 mm ; la moyenne des écoulements mesurés est 129 mm, peu différente de celle des cases cultivées de Versailles : 144 mm pour P = 594 mm (moyenne de 18 ans, il s'agit des anciennes cases) ; pour les 3 cours d'eau britanniques, parmi ceux dont nous connaissons le bilan, dont les précipitations sont les plus proches de celles de Craibstone et de Harrogate qu'elles encadrent, on a respectivement P = 700, D = 231 et P = 927, D = 453 : ces écoulements mesurés encadrent les drainages des cases comme on le vérifie sur le tableau 2 (les évaporations annuelles sont d'environ 390 mm pour les cases et 470 pour le rivières).

Il apparaît donc que pour des cases qui ne s'écartent pas trop des conditions moyennes de la région où elles sont situées, tant par la nature de leur sol que par le développement de la végétation :

1o) le drainage annuel moyen (ou l'évaporation) peut être évalué par la formule (I), sauf lorsque celle-ci est peu satisfaisante pour les rivières elles-mêmes, c'est-à-dire lorsque les précipitations sont fortement concentrées sur quelques mois de l'année ; réciproquement l'écoulement des rivières peut être évalué au moyen des formules établies pour les cases.

2o) le drainage annuel moyen est donc du même ordre que l'écoulement des rivières de la région (les deux grandeurs étant exprimées en hauteur d'eau).

Les accords mis en évidence sont des arguments en faveur des idées suivantes :

— validité des cases lysimétriques pour l'étude des bilans d'eau dans les conditions naturelles, au moins en première approximation.

— rôle prédominant, pour l'alimentation des rivières, des précipitations diminuées de l'eau évaporée par la surface du sol et par les végétaux ; cette théorie est d'ailleurs généralement admise de nos jours.

Applications :

— Au contrôle des cases lysimétriques, comme nous l'avons vu à la fin de l'article précédent : La comparaison des conditions de végétation dans le bassin et dans la case considérés doit guider la comparaison des bilans hydriques ; ainsi l'évaporation en case lysimétrique nue doit être inférieure à celle des bassins naturels de la région, celle des cases couvertes de végétation toute l'année lui est au moins égale et peut lui être bien supérieure ; par exemple, en 1958—59, les nouvelles cases lysimétriques des Versailles portant une luzerne de 3ème année n'ont pas drainé, or l'écoulement des cours d'eau de la région n'était certainement pas nul, mais ces cases contiennent 1m,50 de sol meuble dans lequel le végétal était profondément enraciné, et la récolte annuelle a fourni 1,6 kg de matière sèche par m^2 (16/t/ha) : ces conditions sont évidemment très différentes des conditions moyennes sur une grande surface telle qu'un bassin de cours d'eau.

— A l'analyse de l'alimentation des cours d'eau : Le jaugeage des cours d'eau permet d'établir des bilans pour de longues périodes (plusieurs années), l'établissement de bilans annuels (et non plus annuels moyens) est plus difficile et a fortiori les bilans pour des périodes plus courtes sont mal connus ; les formules établies à partir de l'étude des cases lysimétriques apportent quelques indications dans ce domaine. On peut confronter mois par mois les quantités d'eau qui s'écoulent dans la rivière et les quantités calculées que drainerait une case lysimétrique ; lorsque les premières sont supérieures aux secondes la rivière est alimentée par les réserves du sous-sol (qui dans leur ensemble échappent aux phénomènes d'évaporation), ou par les fontes nivo-glaciaires, pendant les périodes où le classement est inverse ces réserves se rechargent ; on obtient ainsi une évaluation du rôle de ces réserves, un exemple a été donné dans référ. 2 p. 114 et 241 (A. A. 1955 p. 63 et 127).

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LA CUVE LYSIMETRIQUE DE THORNTHWAITE, COMME INSTRUMENT DE MESURE DE L'EVAPOTRANSPIRATION EN REGIONS EQUATORIALES

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SUMMARY

INEAC has organized in 24 of his stations throughout Belgian Congo and Ruanda-Urundi a network of evapotranspiration measurements following the principles involved by THORNTHWAITE.

The installations are composed of two lysimetric pans, 4 m^2 wide.

These pans are planted with Bahia grass (Paspalum notatum) and located in the climatological enclosure. The soil filling the pans is permanently maintained to the field capacity by a regular daily sprinkling.

Installations of the same type are used to measure evapotranspiration either on cropped plants or on grassy formations.

In certain studies on grassy formations of low development, it is cheaper and easier to use, as lysimeters, ordinary 2001 gasoline drums.

If the 4 m^2 pans, can give with a good precision monthly evapotranspiration figures, there are however unsuitable to follow evapotranspiration day by day, except in some where the gain of water is due only to the sprinkling. Some rules to achieve a good installation are discussed.

The practical formula of Penman is satisfactory to give an estimate of the evaporation from a water pan. An empirical formula was established to reach the evaporation in the local conditions of Yangambi starting from new parameters for the aerodynamical expression of the evaporation.

Thornthwaite's equation could not be applied in Belgian Congo because it does take account neither the saturation deficit or the altitude.

RÉSUMÉ

L'INEAC a organisé dans 24 de ses établissements du Congo Belge et du Ruanda-Urundi un réseau de mesure de l'évapotranspiration potentielle et actuelle dans le sens défini par THORNTHWAITE. Les installations comportent deux cuves lysimétriques de 4 m^2 d'ouverture plantées de Paspalum notatum et placées dans l'ambiance de la pelouse du parc climatologique. Le maintien du substrat à saturation est assuré par un arrosage journalier.

Des installations du même type sont utilisées pour mesurer l'évapotranspiration des plantes cultivées ou des formations herbeuses.

Lors d'études comparatives sur l'évapotranspiration des couvertures herbacées à faible développement, les frais expérimentaux peuvent être réduits en utilisant comme cuves lysimétriques des fûts métalliques de 200 l.

Les cuves de 4 m^2 d'ouverture permettent facilement d'obtenir l'évapotranspiration mensuelle, les valeurs journalières ne peuvent être connues avec précision que dans certains cas bien particuliers. L'attention est attirée sur quelques règles d'installation et d'entretien qu'il est indispensable d'observer.

La formule pratique de PENMAN donne satisfaction pour l'estimation de l'évaporation de la nappe d'eau. Une relation empirique a été établie entre cette valeur et l'évapotranspiration potentielle pour les conditions locales. Les paramètres de l'expression aérodynamique de l'évapotranspiration ont été recherchés pour les conditions de Yangambi.

L'équation de THORNTHWAITE ne peut être généralisée pour le Congo Belge. Elle ne tient pas compte des variations du déficit de saturation ni de l'altitude.

1. Description de l'installation standard utilisée dans le réseau de l'INEAC

Dans le cadre de son réseau d'Ecoclimatologie, l'INEAC a organisé dans ses principaux établissements du Congo Belge et du Ruanda-Urundi des installations pour la mesure de l'évapotranspiration potentielle et actuelle.

Le concept de l'évapotranspiration potentielle, défini et commenté par THORNTHWAITE (6,7) est considéré avant tout comme un élément climatique permettant une classification des climats plus en rapport avec l'Ecologie végétale. Il constitue en même temps un outil précieux dans l'abord de nombreux problèmes d'Hydrologie ou de Climatologie Agricole.

Comme toute mesure des éléments du climat, la mesure de l'évapotranspiration potentielle doit répondre à certaines conditions bien précises d'uniformisation, de façon à écarter toute influence perturbatrice, non en rapport avec l'élément mesuré.

L'installation primitivement conseillée par THORNTHWAITE comportant un plan d'eau à niveau constant a été abandonnée par suite des inconvénients que présentait ce système pour le développement de la végétation et les difficultés matérielles de sa réalisation. Actuellement, l'eau nécessaire à l'humidification du substrat est amenée par arrosage.

L'évapotranspiromètre en usage comporte essentiellement trois parties : la cuve lysimétrique, la conduite de vidange et le réservoir de percolation.

La cuve lysimétrique est constituée par un bac en tôles d'acier de 2 m de côté et d'une profondeur moyenne de 70 cm. Le fond comporte un double plan incliné permettant une évacuation rapide des eaux d'infiltration vers un trou de vidange latéral. Les bords supérieurs de la cuve sont renforcés par une cornière soudée extérieurement à 10 cm du sommet. Elle définit en même temps la position de la cuve par rapport au sol environnant.

La cuve d'évapotranspiration est implantée dans la pelouse du parc climatologique. Une couche de gros gravier couvre le fond du bac. Celui-ci, rempli jusqu'à 10 cm du bord supérieur d'une terre représentative du sol de la région, est planté de Paspalum notatum de telle sorte qu'aucune discontinuité n'apparaisse entre la cuve et son entourage.

L'évacuation des eaux d'infiltration se réalise au moyen d'un tuyau à gaz 3/4". Sa pente est d'au moins 3 %. On lui donne la plus grande longueur possible de façon à ce que la cave ne vienne pas perturber l'entourage de la cuve.

Le réservoir de percolation est constitué d'un fût de 200 l comportant, à 5 cm du fond, un robinet de vidange pour la mesure des eaux d'infiltration. A la partie supérieure du réservoir est soudé un mince tube se prolongeant jusqu'au-dessus de la surface du sol. Il permet l'évacuation de l'air du réservoir lors de son remplissage.

Lorsque des difficultés locales empêchent la construction d'une cave, le réservoir de percolation est complètement enterré, les eaux d'infiltration sont alors recueillies par pompage.

L'équipement se complète d'un arrosoir jaugé à 10 l et d'une éprouvette graduée pour la mesure des litres et fractions de litres.

Normalement, les installations réalisées dans les stations du réseau comportent deux évapotranspiromètres de ce type : le premier destiné à la mesure de l'évapotranspiration potentielle, le second, pour l'évapotranspiration actuelle. Vingt-quatre stations sont actuellement équipées de cette manière. (Voir carte.)

De très nombreuses expériences ont montré que la nature de la formation végétale influence, dans une certaine mesure, sa consommation en eau. C'est

pourquoi, d'après THORNTHWAITE, l'évapotranspiromètre standard doit être couvert d'un gazon continu doté d'un albedo d'environ 25 % (8).

Cependant, la notion d'évapotranspiration peut être dégagée de son contexte climatologique pour être appliquée à toute formation végétale dont on veut connaître la consommation en eau dans le cadre d'études hydrologiques ou agricoles. L'évapotranspiromètre de THORNTHWAITE, utilisé tel quel ou adapté au problème étudié, constitue alors un instrument pratique, susceptible d'apporter des solutions valables à ces études. De telles installations sont couramment employées dans les stations de l'INEAC pour la détermination des besoins en eau des cultures vivrières, des couvertures de sidération, des pâturages, et même récemment, des plantes de plus grand développement comme le bananier et le caféier. Pour ces dernières cultures, il est cependant nécessaire d'utiliser des cuves de plus grandes dimensions (3 × 3 × 1,5 m) pour respecter le dispositif normal de plantation et l'intégrité du système radiculaire.

2. Cuves lysimétriques simplifiées pour l'étude de l'évapotranspiration de couvertures herbacées

L'évapotranspiromètre de THORNTHWAITE à 4 m^2 d'ouverture se justifie dans les stations importantes pour l'obtention d'une valeur correcte et uniformisée de l'évapotranspiration potentielle. Cet instrument est cependant relativement coûteux ; sa fabrication ou son acheminement sont souvent trop onéreux dans certaines régions peu développées pour qu'on puisse songer à le multiplier en nombre suffisant pour étudier les multiples strates végétales intéressant l'agronome.

Un type simplifié d'évapotranspiromètre est employé dans ce cas, il s'inspire de l'instrument décrit par M. J. GILBERT (3). On utilise des fûts métalliques de 200 l dont la base portant l'ouverture de remplissage a été découpée proprement. Sur cet orifice de remplissage, se fixe un tuyau galvanisé 2" de 80 cm de long. On prévoit un bouchon à l'extrémité supérieure du tube. L'ensemble est soigneusement enduit de goudron minéral afin de prévenir la rouille.

Sur le fond du fût, on dépose deux blocs de béton de 10 cm de haut sur lesquels reposera le disque de tôle découpé. On détermine ainsi deux compartiments. Dans le compartiment supérieur, on dispose d'abord une couche de gravier de 5 cm que l'on complète avec le sol de culture jusqu'à 5 cm du bord supérieur de la cuve. La formation végétale dont on veut étudier la consommation en eau est alors installée avec les précautions habituelles. Le compartiment inférieur est destiné à recevoir les eaux d'infiltration qui y percolent naturellement par la périphérie du disque à travers la couche de gravier. Ces eaux sont recueillies chaque jour à l'aide d'une pompe à main montée sur un tuyau à gaz 3/4" qui s'introduit dans le tuyau scellé sur le fond du fût. (Voir schéma.)

Cette installation est extrêmement simple à réaliser, elle ne nécessite aucun matériel spécial et exclut tous travaux de soudure qui sont fréquemment à l'origine des fuites survenant dans les autres types de cuves métalliques.

Ce système simplifié ne présente cependant pas la même sécurité que les cuves de grandes dimensions. Comme le montrent les données ci-après résultant d'une année de mesure de l'évapotranspiration potentielle, des écarts assez importants peuvent être enregistrés d'un fût à l'autre, les déviations observées pour chacun des fûts conservant généralement le même sens

Performances des cuves d'évapotranspiration simplifiées
(Evapotranspiration potentielle du gazon en mm/mois.)

	Cuve de 4 m²	Moyenne des 4 fûts	Ecarts par rapport à la moyenne			
			fût n° 1	fût n° 2	fût n° 3	fût n° 4
Janvier	95	109	— 6	+ 3	+ 13	— 10
Février	117	115	— 3	+ 1	+ 16	— 14
Mars	133	130	— 14	— 5	+ 12	— 7
Avril	103	139	— 12	+ 1	+ 15	— 4
Mai	90	113	— 7	+ 3	+ 18	— 14
Juin	104	115	— 8	+ 10	+ 17	— 19
Juillet	68	71	0	— 1	+ 10	— 9
Août	76	84	— 1	+ 1	+ 5	— 5
Septembre	94	94	+ 3	+ 2	— 1	— 4
Octobre	104	98	+ 3	+ 3	+ 5	— 11
Novembre	99	91	0	+ 2	— 1	— 1
Décembre	78	74	+ 3	+ 3	— 1	— 5
Année	1.161	1.233	— 42 (3,4 %)	+ 23 (1,9 %)	+ 108 (8,7 %)	— 89 (7,2 %)

au cours de l'année. La surface d'échantillonnage étant réduite (environ 0,25 m²), on comprend que de faibles différences de sites ou des conditions d'installation peuvent amener des écarts notables dans l'évapotranspiration mesurée. De même, l'irrégularité dans la distribution des pluies ou de légères erreurs lors de la mesure de l'eau d'arrosage ou d'infiltration provoquent des erreurs sur l'évapotranspiration beaucoup plus importantes que lors de l'emploi de cuves de 4 m² d'ouverture.

Un autre inconvénient a été constaté lorsque ces fûts sont utilisés sous une végétation très développée et fort diversifiée telle la végétation de recrû forestier qui s'installe dans les plantations ouvertes par la méthode de non incinération. A ce moment, la répartition de la pluie arrivant à la surface du sol est tellement hétérogène, que les résultats des cuves paraissent complètement abérrants. Dans ces conditions, il est indispensable de multiplier les lysimètres jusqu'à l'obtention d'une moyenne représentative.

Néanmoins, étant donné la modicité des moyens mis en œuvre, la méthode reste très avantageuse lorsqu'on veut étudier in situ, la consommation en eau d'un grand nombre de strates végétales uniformes et peu développées en hauteur.

3. Comportement des cuves lysimétriques installées

Les vingt-quatre installations d'évapotranspiromètres de THORNTHWAITE réalisées jusqu'à présent dans le réseau INEAC donnent, de façon générale, entière satisfaction. Il convient cependant de définir la portée exacte de ces mesures et de signaler les défauts les plus couramment rencontrés au cours des trois années d'expérimentation.

Comme il a été rappelé au début de cette note, l'évapotranspiration potentielle est considérée avant tout comme un élément climatique et le but qu'on s'est proposé est de déterminer l'évolution saisonnière de ce facteur pour les différentes régions naturelles du Congo Belge et du Ruanda-Urundi. La cuve d'évapotranspiration de THORNTHWAITE, installée dans les conditions standardisées précitées convient particulièrement bien pour cet usage.

Cependant, l'évapotranspiration étant essentiellement établie à partir des mesures des précipitations et de percolation — phénomènes se manifestant avec un débit irrégulier — il est nécessaire de tenir compte des pluies importantes survenant en fin des périodes mensuelles. Les corrections doivent s'établir en fonction des vitesses de percolation propres au type de sol utilisé dans la cuve.

Par contre, cet évapotranspiromètre ne convient guère pour les études détaillées où il s'agit de mettre en relation les quantités d'eau consommées par la strate végétale avec d'autres éléments du climat. Pour mener à bien de telles études, dans un minimum de temps, il faut en effet disposer de données se rapportant à des périodes très courtes au cours desquelles les conditions atmosphériques conservent des caractéristiques bien déterminées. Ceci n'est possible que dans les régions à saison sèche de longue durée où la cuve lysimétrique, régulièrement arrosée, permet d'obtenir des valeurs représentatives de l'évapotranspiration quotidienne. L'expérience a montré que dans le cas d'un arrosage journalier et pour des sols légers, où la percolation du surplus se réalise dans les quelques heures qui suivent l'arrosage, il est préférable d'établir l'évapotranspiration du jour à partir de la percolation du surlendemain.

Lors de l'établissement d'un réseau de mesure de l'évapotranspiration, il est absolument indispensable de définir avec la plus grande précision les conditions d'installation et les règles de montage des cuves, certains utilisateurs ne réalisant pas à première vue l'importance de tous les détails. C'est ainsi, qu'à l'usage, il est apparu nécessaire d'insister sur les points suivants :

a) uniformité du couvert végétal dans la cuve et dans son entourage. Ceci postule un apport d'eau en saison sèche sur une superficie d'environ un are autour de la cuve. Par ailleurs, étant donné la pauvreté des réserves chimiques de nombreux sols congolais, il devient indispensable de prévoir une restitution régulière des sels minéraux pour conserver au gazon de la cuve son aspect normal et notamment un albedo voisin de 0,25.
b) horizontalité parfaite de la cuve et de la surface environnante. Ces conditions sont généralement bien respectées au moment de l'installation, cependant, si le terrain a été soumis à un nivellement assez important, il n'est pas rare de voir se produire des affouillements ou un affaissement de la cuve. Lors du placement de la cuve, il convient donc de mettre en œuvre les moyens nécessaires pour lui assurer une stabilité permanente.
c) drainage efficient du fond de la cuve et inclinaison du tuyau de vidange. La non observance de cette règle entraîne un retard dans la percolation et une obstruction progressive de la conduite d'évacuation.
d) étanchéité parfaite du système. L'étanchéité est vérifiée soigneusement lors de l'installation. Pour éviter les déboires ultérieurs toutes les parties métalliques doivent être méticuleusement nettoyées et protégées contre la rouille (goudron minéral). Le robinet de vidange doit être périodiquement vérifié.

Malgré les 10 cm de garde, on constate parfois que la cuve d'évapotranspiration déborde au cours de certaines averses violentes. Ce phénomène induit évidemment une évapotranspiration exagérée pour la période considérée. Il se manifeste sur sol lourd, lorsque la vitesse de percolation devient notablement inférieure à l'intensité de la pluie. L'évapotranspiration étant avant tout conditionnée par les facteurs climatiques, il est avantageux, lors du remplissage de la cuve, de remplacer le sol d'origine, trop compact, par un sol plus léger qui assurera une bonne percolation et des mesures correctes de l'évapotranspiration.

4. Validité des méthodes de détermination de l'évaporation et de l'évapotranspiration dans les conditions locales

L'établissement d'une méthode de détermination de l'évaporation à partir des données climatologiques pour les conditions locales est un des objectifs primordiaux du programme de la Division de Climatologie de l'INEAC. Ces recherches ont déjà reçu un développement sous la direction de E. BERNARD qui a publié récemment une synthèse des travaux réalisés jusqu'à présent dans ce domaine [1]. Il y est démontré que l'analyse de l'évaporation sous l'angle énergétique permet de réaliser d'incontestables progrès dans la recherche des causes globales et directes du phénomène. C'est dans cette voie que sont poursuivies les études actuelles.

La formule pratique de PENMAN [5] pour le calcul de l'évaporation d'une nappe d'eau libre V_w s'exprime par une relation semi-rationnelle déduite du bilan d'énergie

$$V_w = \frac{d.H + A.Va}{d + A} \qquad (1)$$

Dans cette équation, V_w est traduit en chaleur latente d'évaporation consommée par cm² de surface et H, le budget de chaleur qui se confond avec le bilan de rayonnement, s'exprime par la relation

$$H = B = (1 - a)\ G - N \qquad (2)$$

Rappelons que a est l'albedo de la nappe d'eau pour le rayonnement solaire, que G mesure le rayonnement global et que N traduit le rayonnement effectif de la nappe d'eau. Dans la relation (1), A exprime le coefficient psychrometrique, d mesure la pente de la courbe des tensions maxima de vapeur (T, E) au point T_a de la température de l'air, et V_a est une fonction appelée conventionnellement par PENMAN « pouvoir évaporant de l'air ».

$$Va = f(u)\ (E - e) \qquad (3)$$

Dans cette dernière relation, (E — e) est le déficit de saturation de l'air, élément climatologique normalement mesuré dans l'abri. Le facteur f (u) est la fonction de la vitesse du vent observée à un certain niveau dans l'air libre qui intervient dans l'expression aérodynamique de l'évaporation,

$$W_w = f(u)\ (E_s - e) \qquad (4)$$

$(E_s - e)$, mesurant le gradient de la tension de vapeur entre le niveau même de la nappe d'eau, où la tension de vapeur est saturante pour sa température T_s, et un niveau quelconque pris dans l'air libre.

L'équipement de la station centrale de Yangambi permet de mesurer directement les différents termes intervenant dans la formule pratique de PENMAN. L'expression f(u) a été déterminée expérimentalement pour les conditions de Yangambi en observant directement u, V_w et $(E_s - e)$. On trouve [2]:

$f(u) = 0{,}16\ (1 + 0{,}22\ u_2)$, avec u_2 en km/h, V_w en mm et $(E_s - e)$ en mb, (5)
valeur qui diffère assez bien de l'expression établie par PENMAN à Rothmsted: $f(u) = 0{,}26\ (1 + 0{,}146\ u_2)$, ramenée dans les mêmes unités.

Le tableau ci-après compare l'évaporation de la nappe d'eau libre $V_w \cdot c$ calculée d'après la formule (1) à l'évaporation $V_w \cdot m$, réellement mesurée dans un bac de 4 m² d'ouverture, peint intérieurement en noir et complètement enterré. La corrélation est excellente, sauf pour les mois de juin et de juillet.

Valeur de la formule pratique de PENMAN dans les conditions de Yangambi.
Année 1958. Données en mm/mois.

Mois	$V_w \cdot c$	$V_w \cdot m$	$\frac{V_w \cdot c}{V_w \cdot m}$	$V_p \cdot c$	$V_p \cdot m$	$\frac{V_p \cdot c}{V_p \cdot m}$
Janv.	103.2	106.5	0.97	96.4	95.1	1.01
Fév.	103.9	106.1	0.98	97.0	116.9	0.83
Mars	129.6	127.8	1.08	120.6	129.6	0.93
Avril	116.7	108.8	1.07	108.7	103.4	1.05
Mai	105.7	117.9	0.90	98.7	89.5	1.10
Juin	86.4	103.4	0.83	81.1	104.0	0.78
juil.	71.6	84.4	0.85	67.7	68.3	0.99
Août	85.6	91.6	0.93	80.4	76.2	1.05
Sept.	96.3	95.1	1.01	90.1	93.5	0.96
Oct.	104.5	107.2	0.97	97.6	104.3	0.94
Nov.	102.9	110.0	0.93	91.6	98.5	0.93
Déc.	84.6	96.5	0.90	79.5	77.8	1.02
Année	1191.3	1255.3	0.95	1109.2	1157.1	0.96

Pour Yangambi, l'évapotranspiration potentielle du gazon a été reliée expérimentalement à l'évaporation de la nappe d'eau libre par l'expression: [4]

$$V_p = 0{,}91\ V_w + 2{,}5 \text{ en mm/mois} \qquad (6)$$

Les valeurs calculées suivant cette méthode, $V_p \cdot c$, et les valeurs mesurées, $V_p \cdot m$, sont également indiquées à titre de comparaison. On constate que, malgré des écarts mensuels parfois assez conséquents, on obtient néanmoins une très bonne estimation annuelle.

L'expression aérodynamique (4) permet également de déterminer l'evaporation de la nappe d'eau. Elle nécessite toutefois la connaissance de la température superficielle T_s non observable couramment dans les stations climatologiques. En régions tropicales, il existe une bonne corrélation entre T_s et la température de l'air mesurée sous abri T_a. Il est donc simple de remplacer T_s dans E_s (T_s) de la formule (4) par son expression en fonction de la température de l'air sous abri. La droite de régression liant ces deux températures, dans les conditions de Yangambi, a comme équation:

$$T_s = 7{,}2 + 0{,}86\ T_a \qquad (7)$$

La formule aérodynamique dérivée de (4) pour les conditions locales s'écrit donc:

$$V_w = 0{,}16\ (1 + 0{,}22\ u_2)\ \left[(E\ 7{,}2 - 0{,}86\ T_a) - e\right] \text{ en mm/jour.} \qquad (8)$$

Les valeurs calculées suivant cette méthode sont consignées ci-après. L'évaporation ainsi trouvée est en général légèrement inférieure à l'évaporation obtenue à partir de la formule pratique de PENMAN, on obtient par contre des valeurs beaucoup plus proches de la réalité pour les mois de juin et de juillet.

THORNTHWAITE (7), en 1948, proposait une équation générale pour le calcul de l'évapotranspiration potentielle basée sur la température de l'air et la durée d'insolation possible :

$$e = 1{,}6\ (10.T\ /\ I)^a$$

expression dans laquelle, e exprime l'evapotranspiration mensuelle, T, la température moyenne mensuelle, I représente un « indice thermique » déter-

Valeur de la formule aérodynamique adaptée aux conditions de Yangambi
Année 1958. Données en mm/mois.

Mois	$V_w \cdot c$	$V_w \cdot m$	$\frac{V_w \cdot c}{V_w \cdot m}$	$V_p \cdot c$	$V_p \cdot m$	$\frac{V_p \cdot c}{V_p \cdot m}$
Janv.	101.6	106.5	0.95	95.0	95.1	1.00
Fév.	101.6	106.1	0.96	95.0	116.9	0.81
Mars	116.9	127.8	0.91	108.9	129.6	0.84
Avril	102.0	108.8	0.04	95.3	103.4	0.92
Mai	106.0	117.9	0.90	99.0	89.5	1.11
Juin	95.7	103.4	0.93	89.6	104.0	0.86
juil.	86.8	84.4	1.03	81.5	68.3	1.19
Août	92.4	91.6	1.01	86.6	76.2	1.14
Sept.	93.0	95.1	0.98	87.1	93.5	0.93
Oct.	99.5	107.2	0.93	93.0	104.3	0.89
Nov.	98.7	110.0	0.90	92.3	98.5	0.94
Déc.	87.7	96.5	0.91	82.3	77.8	1.06
Année	1181.9	1255.3	0.94	1105.6	1157.1	0.96

miné à partir des températures moyennes mensuelles et a, indique un coefficient calculé en fonction de l'indice thermique.

L'auteur, tout en reconnaissant l'empirisme et la faiblesse de cette expression, soutient toutefois qu'elle permet d'arriver à des valeurs quasi correctes de l'évapotranspiration, valeurs qui peuvent intervenir pour résoudre les problèmes de la classification des climats.

Nous avons repris en annexe, pour quelques stations du réseau, les valeurs de l'évapotranspiration calculées suivant l'équation de THORNTHWAITE en regard de l'évapotranspiration réellement mesurée. Sur la base de ces comparaisons, de graves reproches peuvent être formulés contre cette expression de l'évapotranspiration potentielle. Elle ne tient aucun compte en effet, des variations du déficit de saturation, caractéristique physique agissant directement sur l'évaporation, indépendamment de la température. C'est ainsi que pour les stations de latitude équatoriale, où la température de l'air varie peu au cours de l'année, l'évapotranspiration est surestimée au cours des périodes humides. Elle est égale ou inférieure à l'évapotranspiration mesurée durant les mois secs, suivant que la station est soumise ou non à des vents desséchants.

Trois exemples de stations d'altitude sont également indiqués. Dans ces régions, la relation liant le bilan de rayonnement, la température de l'air et le déficit de saturation diffère fortement de ce qui a été établi pour les conditions d'altitude moyenne ou basse. L'équation de THORNTHWAITE n'est pas d'application pour ces régions élevées. Elle ne rend compte que d'une façon incomplète de l'évapotranspiration réellement mesurée.

Ces résultats ne sont cités ici qu'à titre d'illustration. Les travaux actuels de la Division de Climatologie s'orientent presqu'exclusivement vers les méthodes découlant de la théorie du bilan d'énergie. On s'efforce de rassembler les données d'observation et d'établir les paramètres particuliers qui permettront l'application de la formule pratique de PENMAN à toutes les régions naturelles du Congo Belge et du Ruanda-Urundi.

Valeurs de l'équation de Thornthwaite pour l'estimation de l'évapotranspiration potentielle pour quelques Stations du Congo Belge et du Ruanda-Urundi

YANGAMBI (N. 0°49' E. 24°27' 487 m)

	1957			1958			1957—1958		
	Evapotr. calculée	Evapotr. mesurée	Rapport. %	Evapotr. calculée	Evapotr. mesurée	Rapport. %	Evapotr. calculée	Evapotr. mesurée	Rapport. %
J.	106.3	94.8	112	121.2	95.1	127	113.7	95.1	119
F.	104.0	97.2	107	106.7	116.9	91	105.3	107.0	98
M.	116.5	109.8	106	130.5	129.6	101	123.5	119.7	103
A.	117.7	124.8	94	125.2	103.4	121	121.5	114.1	107
M.	121.2	84.7	143	124.3	89.5	139	122.7	87.1	141
J.	111.7	91.7	122	111.7	104.0	107	111.7	97.9	115
J.	110.6	86.2	128	122.7	68.3	180	116.7	77.3	154
A.	104.8	71.5	147	100.7	76.2	132	102.7	73.9	139
S.	106.0	88.2	120	103.2	93.5	110	104.6	90.9	115
O.	104.8	103.2	101	112.1	104.3	107	108.5	103.7	104
N.	111.7	103.7	108	114.6	98.5	116	113.1	101.1	112
D.	106.3	65.0	163	110.7	77.8	142	108.5	71.4	153
A.	1321.6	1120.8	118	1383.6	1157.1	119	1352.6	1139.2	119

BAMBESA (N. 3°27' E. 25°43' 621 m)

	1957			1958			1957—1958		
	Evapotr. calculée	Evapotr. mesurée	Rapport. %	Evapotr. calculée	Evapotr. mesurée	Rapport. %	Evapotr. calculée	Evapotr. mesurée	Rapport. %
J.	93.2	130.8	71	106.7	103.0	104	99.9	116.9	87
F.	87.3	108.7	80	97.7	114.2	85	92.5	111.5	83
M.	107.2	86.8	123	121.5	121.2	100	114.3	104.0	111
A.	113.3	111.5	102	126.5	144.0	88	119.9	127.7	95
M.	117.8	105.1	112	123.5	111.6	111	120.7	108.3	111
J.	102.9	131.6	78	102.4	100.4	102	102.7	116.0	90
J.	103.4	95.8	108	96.6	94.6	102	100.0	95.2	105
A.	104.0	91.1	114	95.3	123.6	77	99.7	107.3	95
S.	106.5	104.4	102	100.4	95.5	105	103.5	99.9	103
O.	99.1	111.3	89	105.3	108.7	97	102.2	110.0	93
N.	105.5	100.6	105	106.4	95.5	111	105.9	98.1	108
D.	99.1	96.5	103	108.1	90.2	120	103.6	93.3	111

Valeur de l'équation de Thornthwaite pour l'estimation de l'évapotranspiration potentielle pour quelques Stations du Congo Belge et du Ruanda-Urundi

BONGABO (N. 3°06' E. 20°32' 450 m)

	1957			1958			1957—1958		
	Evapotr. calculée	Evapotr. mesurée	Rapport. %	Evapotr. calculée	Evapotr. mesurée	Rapport. %	Evapotr. calculée	Evapotr. mesurée	Rapport. %
J.	98.9	94.4	105	125.1	100.9	124	111.5	97.7	115
F.	101.8	97.4	105	114.4	102.9	111	108.1	100.1	108
M.	120.5	114.7	105	144.6	103.6	140	132.5	109.1	123
A.	125.5	124.1	101	137.7	91.1	151	131.6	107.6	126
M.	135.1	88.6	153	135.5	94.6	143	135.3	91.6	148
J.	120.5	79.2	152	114.3	74.0	155	117.4	76.6	153
J.	—	—	—	107.1	68.4	157	(107.1)	(68.4)	(157)
A.	113.4	75.8	150	111.8	79.1	141	112.6	77.5	145
S.	115.1	82.5	139	118.2	84.0	141	116.7	83.3	140
O.	115.9	86.7	134	114.3	110.2	104	115.1	98.5	119
N.	111.0	73.3	151	112.5	74.7	151	111.7	74.0	151
D.	109.7	73.2	150	117.4	85.7	137	113.5	79.5	143
A.	1267.4	989.9	131	1452.9	1069.2	136	1413.1	1063.9	136

M'VUAZI-VALIEE (S. 5°27' E. 14°54' 465 m)

	1957			1958			1957—1958		
	Evapotr. calculée	Evapotr. mesurée	Rapport. %	Evapotr. calculée	Evapotr. mesurée	Rapport. %	Evapotr. calculée	Evapotr. mesurée	Rapport. %
J.	113.3	79.7	142	119.3	77.8	153	116.3	78.7	148
F.	106.9	96.6	111	111.1	107.0	104	109.0	101.8	107
M.	118.6	119.0	100	131.0	112.2	117	124.8	115.6	108
A.	124.5	112.1	111	121.5	109.3	111	123.0	110.7	111
M.	119.3	111.4	107	103.4	81.8	126	111.3	96.6	115
J.	70.3	79.5	88	59.4	68.5	87	64.9	74.0	88
J.	56.5	58.7	96	47.4	61.1	78	51.9	59.9	87
A.	69.0	73.3	94	61.8	70.9	87	65.4	72.1	91
S.	92.7	85.7	108	84.6	85.6	99	88.7	85.7	103
O.	104.9	92.8	112	112.2	96.3	117	108.5	94.5	115
N.	113.0	101.5	111	115.9	90.6	128	114.5	96.1	119
D.	112.4	88.2	127	130.4	83.4	156	121.4	85.8	141
A.	1201.4	1098.5	109	1197.6	1044.5	115	1199.5	1071.5	112

Valeurs de l'équation de Thornthwaite pour l'estimation de l'évapotranspiration potentielle pour quelques Stations du Congo Belge et du Ruanda-Urundi

KIYAKA (S. 5°16' E. 18°57' 735 m)

	1957			1958			1957—1958		
	Evapotr. calculée	Evapotr. mesurée	Rapport. %	Evapotr. calculée	Evapotr. mesurée	Rapport. %	Evapotr. calculée	Evapotr. mesurée	Rapport. %
J.	97.1	85.6	113	120.3	121.1	99	109.7	103.5	106
F.	92.4	79.3	117	102.4	91.9	111	97.4	85.6	114
M.	98.8	89.2	111	119.6	104.0	115	109.2	96.6	113
A.	101.3	89.4	113	113.5	138.2	82	107.4	113.8	97
M.	107.6	101.0	107	120.4	106.6	113	114.0	103.8	110
J.	108.6	102.6	106	102.6	97.3	105	105.6	99.9	105
J.	110.5	92.4	120	96.3	89.4	108	103.4	90.9	114
A.	110.1	98.8	111	111.0	106.3	104	110.5	102.5	107
S.	104.1	100.0	104	116.5	118.1	99	110.3	109.1	101
O.	98.6	100.6	98	107.3	97.5	110	102.9	99.1	104
N.	101.5	87.0	117	102.4	95.4	107	101.9	91.2	112
D.	103.1	107.3	96	109.8	78.8	139	106.5	93.1	117
A.	1233.7	1133.2	109	1322.1	1244.6	106	1277.9	1188.9	107

GANDAJIKA (S. 6°45' E. 23°57' 780 m)

	1957			1958			1957—1958		
	Evapotr. calculée	Evapotr. mesurée	Rapport. %	Evapotr. calculée	Evapotr. mesurée	Rapport. %	Evapotr. calculée	Evapotr. mesurée	Rapport. %
J.	111.3	94.3	118	117.2	110.9	106	114.3	102.6	112
F.	92.0	76.6	120	103.7	111.0	93	97.9	93.8	107
M.	103.4	111.5	93	119.6	125.9	95	111.5	118.7	94
A.	105.0	96.9	108	113.5	124.5	92	109.3	110.7	100
M.	102.8	106.9	96	109.9	121.2	91	106.3	114.1	93
J.	91.3	116.8	78	97.4	110.0	89	94.3	113.4	83
J.	96.3	120.5	80	92.6	110.0	84	94.5	115.3	82
A.	113.9	124.1	92	97.2	90.7	107	105.5	107.4	99
S.	100.8	130.9	77	105.0	113.9	92	102.9	122.4	85
O.	102.9	124.9	82	110.3	126.5	87	106.6	125.7	85
N.	108.1	119.1	91	109.6	121.2	90	108.9	120.1	91
D.	110.9	105.7	105	110.9	123.8	90	110.9	114.7	97

... pour l'estimation de l'évapotranspiration potentielle pour quelques Stations du Congo Belge et du Ruanda-Urundi

KEYBERG (S. 11°44' E. 27°25' 1187 m)

	1957			1958			1957—1958		
	Evapotr. calculée	Evapotr. mesurée	Rapport. %	Evapotr. calculée	Evapotr. mesurée	Rapport. %	Evapotr. calculée	Evapotr. mesurée	Rapport. %
J.	93.1	104.3	89	101.0	96.7	104	97.1	100.5	97
F.	83.7	84.6	99	91.9	101.3	91	87.8	92.9	95
M.	89.7	102.2	88	95.4	100.3	95	92.5	101.3	91
A.	76.2	110.2	69	81.8	105.1	78	79.0	107.7	73
M.	53.0	111.4	48	53.0	110.9	48	53.0	111.1	48
J.	18.5	89.7	21	39.8	80.9	49	29.1	85.3	35
J.	41.5	79.9	52	32.0	72.5	44	36.7	76.2	48
A.	58.1	95.0	61	47.0	81.1	58	52.7	88.1	59
S.	80.9	125.1	65	85.3	110.4	77	83.1	117.7	71
O.	108.4	143.0	76	100.4	141.0	71	104.4	142.0	73
N.	110.3	152.8	72	105.3	144.9	73	107.8	148.9	73
D.	103.0	106.6	97	102.0	98.8	103	102.5	102.7	100
A.	916.4	1304.8	70	934.9	1243.9	75	925.7	1274.3	73

KISOZI (S. 3°33' E. 29°41' 2155 m)

	1957			1958			1957—1958		
	Evapotr. calculée	Evapotr. mesurée	Rapport. %	Evapotr. calculée	Evapotr. mesurée	Rapport. %	Evapotr. calculée	Evapotr. mesurée	Rapport. %
J.	60.2	66.2	91	67.7	85.8	79	63.9	76.0	85
F.	56.7	62.8	90	59.9	72.9	82	58.3	67.9	86
M.	62.7	82.8	76	65.0	89.5	73	63.9	86.1	75
A.	59.1	81.2	73	62.5	86.1	73	60.8	83.7	73
M.	59.6	68.6	87	58.4	90.9	64	59.0	79.7	75
J.	49.5	82.5	60	48.3	74.7	65	48.9	78.6	63
J.	49.7	90.1	55	50.9	97.2	52	50.3	93.7	53
A.	59.0	101.2	58	55.9	97.1	58	57.5	99.1	58
S.	69.9	132.8	53	63.1	105.7	60	66.5	119.3	57
O.	69.6	92.3	75	65.6	115.2	57	67.6	103.7	66
N.	65.2	75.8	86	64.4	98.2	66	64.8	87.0	76
D.	67.1	72.9	92	62.3	78.0	80	64.7	75.5	86
A.	728.3	1009.2	72	724.0	1091.3	66	726.1	1050.3	69

Valeurs de l'équation de Thornthwaite pour l'estimation de l'évapotranspiration potentielle pour quelques Stations du Congo Belge et du Ruanda-Urundi

MUSASA (S. 3°39' E. 30°21' 1260 m)

	1957			1958			1957—1958		
	Evapotr. calculée	Evapotr. mesurée	Rapport. %	Evapotr. calculée	Evapotr. mesurée	Rapport. %	Evapotr. calculée	Evapotr. mesurée	Rapport. %
J.	82.2	124.1	66	89.3	151.6	59	85.7	137.9	63
F.	77.1	97.5	79	78.0	121.8	64	77.5	109.7	71
M.	81.4	142.4	57	88.4	142.9	62	84.9	142.7	59
A.	78.3	138.3	57	87.0	135.4	64	82.7	136.9	61
M.	80.6	115.1	70	78.8	96.7	81	79.7	105.9	75
J.	63.8	94.8	67	65.4	106.0	62	64.6	100.4	65
J.	61.6	101.4	61	65.7	141.9	46	63.7	121.7	53
A.	76.9	102.3	75	83.6	120.2	69	80.3	111.3	72
S.	95.0	137.3	69	97.1	139.2	70	96.1	138.3	69
O.	105.3	139.7	75	103.0	157.4	65	104.1	148.5	70
N.	99.0	143.5	69	95.9	159.1	60	97.5	151.3	65
D.	89.3	138.1	65	88.3	109.0	81	88.8	123.5	73
A.	990.5	1474.5	67	1020.5	1581.2	65	1005.5	1527.9	66

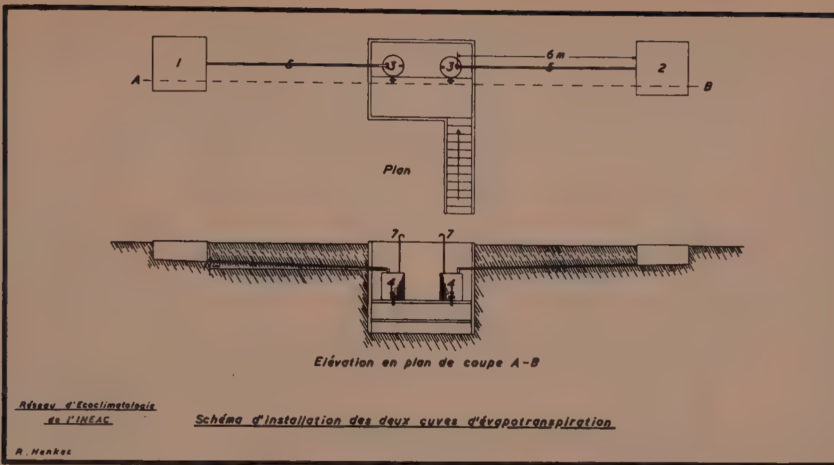
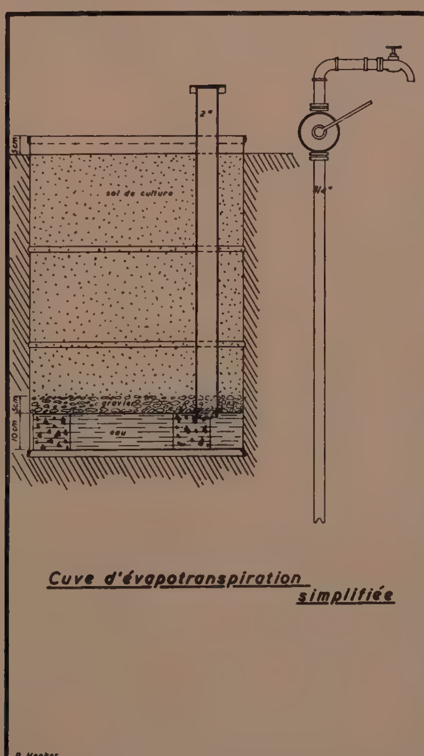


Schéma d'installation des deux cuves d'évapotranspiration



Cuve d'évapotranspiration simplifiée

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SUR UNE TECHNIQUE DE MESURE DE L'EVAPOTRANSPIRATION POTENTIELLE ET ACTUELLE DE CULTURES

par A. RINGOET

Division de Physiologie végétale de l'Institut National pour l'Etude Agronomique du Congo Belge (I.N.E.A.C.) à YANGAMBI

SUMMARY

A technical method is proposed which allows to measure potential and actual evapotranspiration of annual crops and herbaceous plant associations, in normal ecological growth conditions by daily weighing of the pots, placed on low easily manageable waggons.

RÉSUMÉ

La technique proposée permet la mesure de l'évapotranspiration potentielle ou actuelle par pesées quotidiennes de vases de culture placés sur des wagonnets très maniables. —

Cette méthode s'applique dans sa forme actuelle, à des cultures de plantes annuelles et éventuellement à des associations végétales herbacées. —

Deux types d'installations, qui permettent à ces couverts végétaux de croître dans une ambiance écologique normale, sont décrits.

I. — INTRODUCTION

Dans le cadre des études écologiques du bilan d'eau qui se poursuivent à Yangambi, la Division de Physiologie végétale s'intéresse depuis des années à la mesure de la transpiration des végétaux. —

Jusqu'en 1952, la mesure fut réalisée par la pesée de plantes isolées en vases de végétation de format réduit (RINGOET, 3). —

Les études publiées par PENMAN (2) qui considèrent le problème de l'évapotranspiration sous l'angle du bilan énergétique, ont conduit à une révision complète des techniques de mesure de la transpiration. En effet, l'une des conclusions d'ordres physiologique et agronomique les plus intéressantes de la méthode de PENMAN est la différence importante entre les pertes d'eau par transpiration de plantes isolées et de plantes semblables à l'état groupé (BERNARD 1).

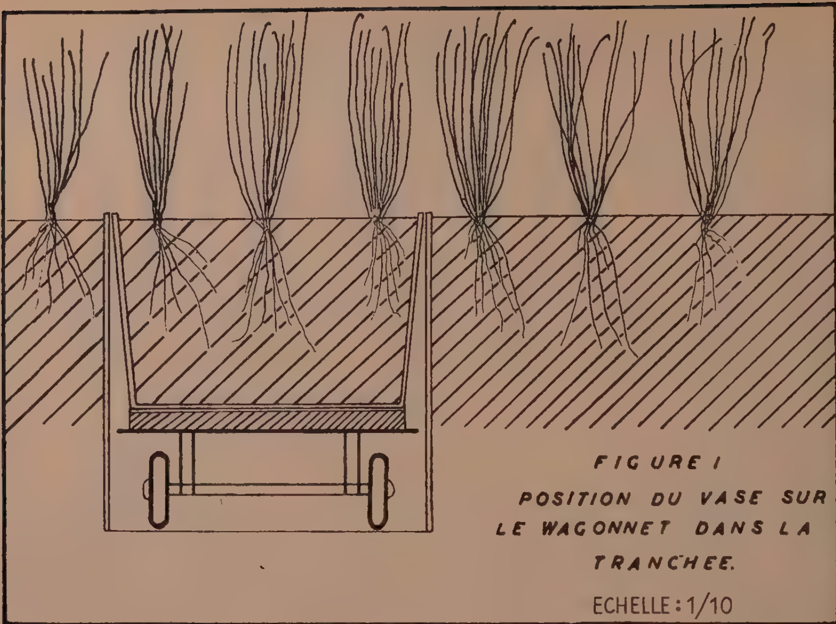
Le chapitre suivant est consacré à la description d'une technique simple qui permet la mesure de l'évapotranspiration potentielle et actuelle de cultures de riz, de soja et de maïs (4, 5, 6) dans leurs ambiances culturales normales. —

Dans ce texte on entend par *évapotranspiration* la perte d'eau globale en mm par transpiration des végétaux et par évaporation de la surface du sol.

Les termes évapotranspiration *potentielle* et évapotranspiration *actuelle* se définissent comme suit :

— l'évapotranspiration potentielle exprime les pertes en eau d'une culture dont le substrat est maintenu à la capacité au champ (field capacity)

— l'évapotranspiration actuelle se rapporte aux quantités d'eau perdues par une culture en milieu édaphique non saturé en eau. —



II. — Technique proposée

a) *modèle et utilisation des vases de culture.*

Les plantes sont cultivées dans des vases, en éternit, de forme parallélipipédique dont les dimensions sont les suivantes :
100 × 75 × 50 (profondeur) cm.

Les parois des vases ont environ 2 cm d'épaisseur et le fond est renforcé. Ces parois sont enduites d'un produit anticorrosif.

Les vases sont remplis du substrat choisi pour l'essai. Ce substrat repose sur une couche de 10 cm de gravier permettant éventuellement le drainage d'un surplus d'eau. Celle-ci réduit la profondeur du substrat à 40 cm, ce qui suffit encore largement à l'enracinement de la plupart des cultures et des associations végétales herbacées éventuellement prises en considération.

Les vases sont placés sur des wagonnets métalliques plats de 20 cm de hauteur et dont le plateau présente les mêmes dimensions que le fond des vases de culture. Les wagonnets sont équipés de trois roues ; celle située à l'avant, orientable dans tous les sens, rend le wagonnet très maniable. Grâce à cette maniabilité deux hommes déplacent aisément un wagonnet.

On dispose de 60 wagonnets et vases de ce modèle (figure 1).

b) *Installation permettant la réalisation de la culture « continue en champ fermé »*

1. — Premier type d'installation

Les ensembles (vases + wagonnets) sont placés côte à côte (6 rangées de 10 vases) sur une aire bétonnée.

La surface cultivée, constituée par le groupement de ces vases, est étendue latéralement par deux soles de culture dont le substrat est retenu

par une mince (5 cm) paroi de béton armé. Le bord supérieur de la paroi en béton arrive au même niveau que le sommet des vases (figure 2).

Les vases extrêmes de chaque rangée ferment le « champ ».

Les 48 vases centraux constituent les éléments de base du champ expérimental.

2. — Second type d'installation

Les ensembles (vases + wagonnets) sont alignés au nombre de six dans des tranchées à entrée unique. Le sixième vase délimite le « champ ». Le bord supérieur des vases de culture affleure le niveau du sol en place entre les tranchées (figure 1).

Le semis ou la plantation à densité normale dans les vases et dans les soles de bordure permet de constituer un champ de culture réel ou de reproduire une végétation naturelle. —

L'étude de l'évapotranspiration actuelle exige le contrôle des apports d'eau et par conséquent l'élimination de l'influence de la pluie. Dans ce but chacune des installations décrites ci-dessus peut être réalisée sous abri mobile.

Ainsi, en dehors des périodes de pluie, les plantes peuvent être exposées à la radiation normale incidente. —

c) *Mesure de l'évapotranspiration*

Les installations décrites ci-dessus sont reliées à l'emplacement abrité d'un pont-bascule par de larges (2 m) bandes de roulement en béton.

Tous les matins entre 6 et 7 heures, les wagonnets sont amenés sur la bascule, pesés, et, selon les traitements, la réserve hydrique du substrat est réajustée à la capacité au champ par un apport contrôlé d'eau. Ensuite les wagonnets sont ramenés à leur place dans l'installation. La durée du séjour de chaque vase de culture en dehors de l'ambiance culturale normale ne dépasse pas quelques minutes.

L'évapotranspiration actuelle se mesure par la différence entre les pesées quotidiennes.

L'évapotranspiration potentielle est égale à la différence entre le poids à la capacité au champ et la pesée du jour. —

La bascule utilisée à Yangambi, a une portée de 1000 kg, à lecture sur cadran de 100 kg, gradué en 0,1 kg. La précision obtenue est suffisante.

La figure 3 représente schématiquement les deux types d'installations et l'emplacement du pont-bascule.

III. — Intérêt de la technique proposée

La technique de mesure de l'évapotranspiration décrite présente l'avantage d'utiliser un grand nombre de vases, et par conséquent de considérer plusieurs traitements à nombre suffisant de répétitions.

Les pesées quotidiennes permettent de mesurer avec précision l'évapotranspiration actuelle et potentielle d'une culture, ce qui présente un avantage considérable par rapport aux lysimètres à mesure du percolat. Si nécessaire, plusieurs observations peuvent être faites au cours de la journée. —

La mobilité des vases permet l'utilisation d'un pont-bascule de fabrication courante, ce qui n'est pas le cas dans les installations lysimétriques à bascule mobile.

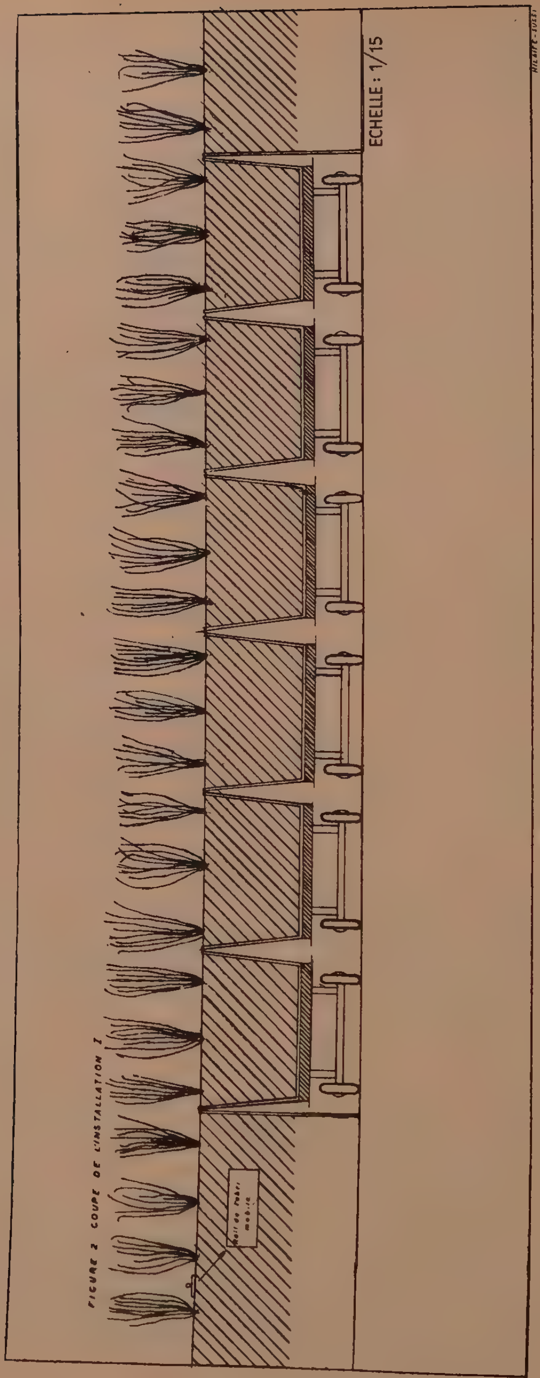


FIGURE 2 COUPE DE L'INSTALLATION I

La technique, sous sa forme actuelle, ne se prête qu'à des études sur plantes annuelles ou sur associations végétales herbacées.

La méthode présente de plus l'inconvénient de faire appel à un personnel nombreux. Celui-ci pourrait utilement être remplacé grâce à l'emploi de petits tracteurs.

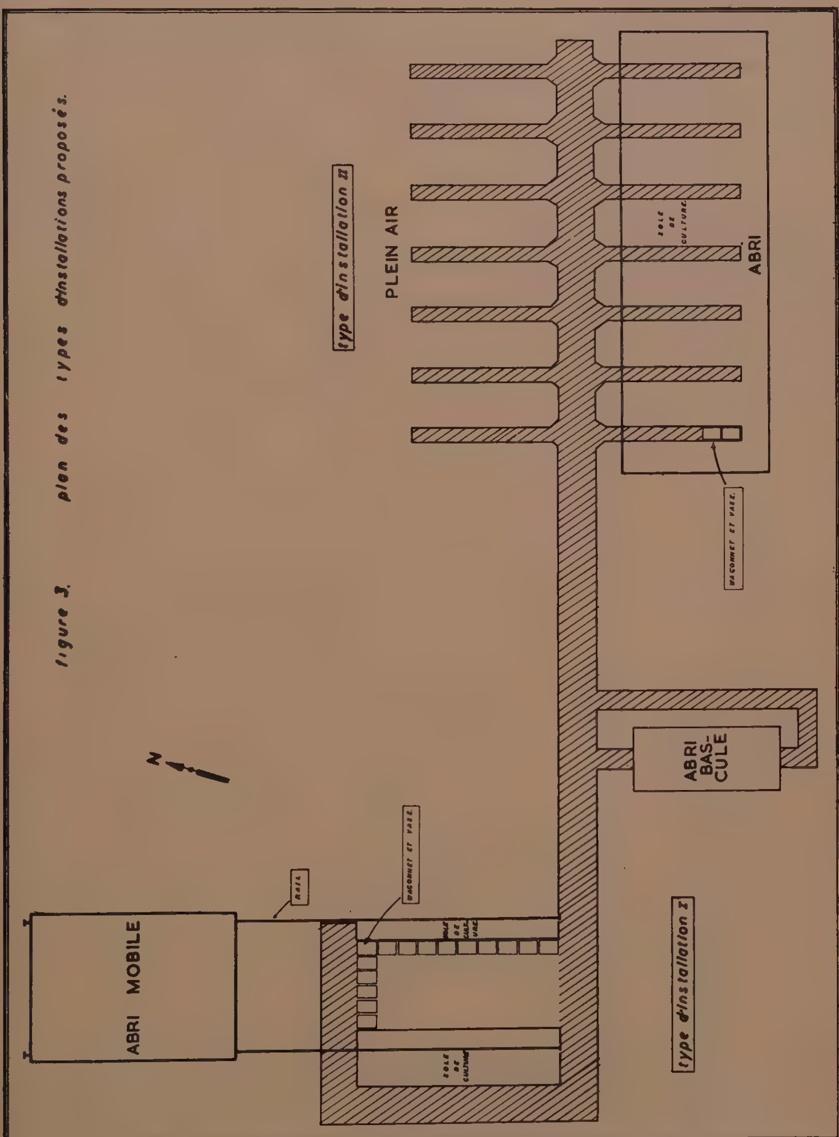


figure 3. plan des types d'installations proposés.

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"WEIGHING MONOLITH LYSIMETERS AND EVALUATION OF AGRICULTURAL HYDROLOGY"

by L. L. HARROLD and F. R. DREIBELBIS

SUMMARY

This paper presents a brief description of the major features of the Coshocton lysimeters along with some of the unusual details of data tabulation, computation, and compilations. The self-recording feature of these lysimeters, including the unique weighing mechanism, makes it possible to evaluate the various forms of accretion and depletion of soil moisture as well as water-storage changes within the natural soil block. These data have and are continuing to supply evaluations needed in the solution of numerous problems in agricultural hydrology.

RÉSUMÉ

Cet article donne une brève description des principales caractéristiques des lysicompteurs Coshocton, en même temps que quelques détails inhabituels sur les données de tabulation, d'estimation et des compilations. La caractéristique de self-enregistrement de ces lysicompteurs, comprenant l'unique mécanisme de pesage, a permis d'évaluer les diverses formes d'accroissement ou de diminution de l'humidité du sol aussi bien que les changements de réserves d'eau à l'intérieur du bloc naturel du sol. Ces données ont suppléé et continuent de suppléer les evaluations nécessaires de résoudre de nombreux problèmes d'hydrologie agricole.

The lysimeters of the United States Department of Agriculture Soil and Water Conservation Research Station (2) near Coshocton, Ohio, have been in full operation since 1944, though several of the individual lysimeters have been in operation since the late 1930's. The lysimeters were designed primarily for evaluating agricultural hydrology. They are of unique design—deep enough to extend three feet into the shale or sandstone rock. Natural transmission of soil water from the subsoil to the rock cracks is thus achieved without applying tension.

No attempt is made here to review the literature on lysimetry. This was previously done by Kohnke et al (4) (3) in which two and a half centuries

Construction

of lysimeter research were reviewed up to 1939. Some of the later work up to 1955 was reviewed by the authors (3).

The surface soil area of each lysimeter is 0.002 acre, 6.22 feet wide and 14.00 feet long up the slope. Side walls of 8-inch concrete extend 8 feet below the ground surface. These walls, forming a rectangle of the above dimensions and having a beveled cutting edge at the bottom, were built on top of the ground. They were gradually lowered as a unit into a trench as it was excavated without disturbing the enclosed soil. At the 8-foot depth, steel plates were forced through the rock to form the bottom of the lysimeter.

(1) Project Supervisor and Soil Scientist, respectively, Soil and Water Conservation Research Division, Agricultural Research Service, Coshocton, Ohio.

(2) Operated by U. S. Department of Agriculture in cooperation with the Ohio Agricultural Experiment Station.

(3) Numbers in parenthesis refer to literature cited.

These plates had been perforated to permit free passage of percolating water to collection pipes and on into a measuring tank.

Runoff from uphill areas is diverted around the lysimeter. Runoff from the 0.002-acre area drops into a trough at the end and drains into a collection tank. Automatic water-depth recorders operate on both the runoff and percolation tanks.

Eleven lysimeters of this type were installed at three different sites on the station. Automatic print-weight scales were placed beneath one lysimeter at each site. Weight figures are printed every 10 minutes. On a gross weight of about 65 tons, these scales have an accuracy of 5 pounds—equivalent to about 0.01 inch of water over the lysimeter surface. Grease placed in the narrow cup-shaped gap separating the movable lysimeter from the surrounding soil at the ground surface permits the weighing lysimeters to move freely. Furthermore, it prevents air and water from entering the shelter tunnel below the surface. The temperature of the lysimeter soil and of the air in the tunnel is thus maintained the same as soil temperature in adjacent crop fields.

Management, Soils and Climate

Of the eleven lysimeters, seven are cultivated in a 4-year rotation of corn, wheat, meadow, meadow. The other four are in continuous pasture grass and legume-grass mixtures; from these the crop is removed by occasional clipping. No livestock grazing has been permitted. The eleven lysimeters are grouped into three different sites on the station as follows:

Y101. — *Four lysimeters* on well drained Muskingum silt loam over sandstone, 23.2 per cent slope, pasture grass. Elevation 1245 feet.

Y102. — *Three lysimeters* on well drained Muskingum silt loam over shale, 12.9 per cent slope, 4-year crop rotation of corn, wheat, meadow, meadow in conservation practice. Elevation 1200 feet.

Y103. — *Four lysimeters* on slowly permeable Keene silt loam over shale, 6.0 per cent slope, same 4-years crop rotation, poor practices on two, conservation practices on other two. Elevation 1130 feet.

A complete description of the soils appears in the Appendix.

The cultural and fertility treatment of the soil on the lysimeters has been the same as that in the surrounding farm areas. Hand tools are used in working the lysimeter soils. Tractor-drawn farm equipment has operated up to the edge of the lysimeters. The entire crop on each lysimeter is removed at the regular harvest time and yield determinations made. Full details of these operations for the years 1936 to 1955 have been published (3).

The climate in the Coshocton, Ohio area is characterized normally by abundant precipitation, well distributed throughout the year. The average annual precipitation is about 40 inches. Summer temperatures are rather high but not unduly oppressive, while winter temperatures are not severe and snowfall is generally moderate. The maximum and minimum temperatures recorded for a 23-year period for Coshocton are 106° and —26° F, respectively. The average period between killing frosts extends from May 3 to October 12, the length of the growing season averaging about 162 days. The depth of frost penetration on corn or wheat fields reaches 6 to 10 inches at some time during the average winter. The period of record, 1944—57, has been found to be quite representative of the long-term climate of the area.

Processing of data

From the weight figures, which are printed at 10 minute intervals, six consecutive values are averaged to provide hourly data for tabulation of daily summaries. A sample daily weight summary for a typical period in 1949 appears in Table 1. As these figures have been adjusted for tare, they do not represent the total weight of the lysimeter.

Water changes such as evapotranspiration can be derived directly from these hourly weight data. Daily storage-change values are obtained by subtracting the initial 0000-hour reading from the final 2400-hour reading in pounds and converting this value to inches of water by multiplying by 0.002207. Weight changes for the period of the day when the lysimeter consistently loses weight, are converted into inches of water, adjusted for concurrent percolation and runoff amounts, and labeled ET, or evapotranspiration. Likewise, consistent gains are evaluated and labeled CA, or condensation-absorption. During periods of precipitation, as defined by a recording rainage, ET and CA are assumed to be zero.

On November 22, 1949 (Table 1) loss of weight persisted from 0700 hour to 1200 and from 1800 to 2200 totaling 43.1 pounds. Multiplying this value by 0.002207, ET of 0.095 inch of water is obtained. Weight gains prevailed from 0000 to 0700 hour, from 1200 to 1800, and from 2200 to 2400 totaling 23.9 pounds. CA is thus evaluated as 0.053 inch of water. ET-CA or net loss of moisture storage for the day of 0.042 inch of water (0.095—0.053) is commonly referred to as *consumptive use.*

The weighing lysimeter is an excellent rainage. Its area is 12,540 square inches. That of the weighing rainage is only 50 square inches. Weight increases on the lysimeter for the duration of each storm (taken from the rainage chart) are converted to inches of water and adjusted for concurrent runoff and percolation. Snowfall data are likewise evaluated on the lysimeter. There appears to be no significant difference in storm rainfall totals as evaluated by the rainage and the weighing lysimeter. Noticeable differences, however, have occurred in measurements of snowfall. The lysimeter values have been greater than those from an unshielded rainage.

There are certain limitations in the Coshocton lysimeters as with all lysimeters. Concrete walls form an artificial boundary that restricts lateral movement of water in the soil. Some of the lysimeter vegetation overhangs the boundaries, thus developing an area for transpiration slightly larger than 0.002 acre. Compaction of the lysimeter soil by workmen and the use of hand tools has probably been less than that developed in surrounding fields by mechanized farm equipment. The lysimeter conditions, however, approach nature as closely as possible. The hydrologic evaluations are therefore believed to be the most reliable of their kind to date.

Evaluations

Examples of various hydrologic evaluations that can be developed from the lysimeter operations are given below.

Monthly accretion, depletion, and storage of soil moisture

These evaluations for all three weighing lysimeters are available, starting in 1944. A sample tabulation appears in Table 2.

Percolation occurred mostly in the period of February to May. This is the cool, wet season in Ohio. Soil moisture usually exceeded the holding capacity of the soil profile at that season and drainage by gravity occurred.

TABLE 1.—*Sample of hourly weight data and daily hydrologic summary values November 21-23, 1949*

Hour	November 21	November 22	November 23
	Pounds	Pounds	Pounds
0000	1796.8	1785.0	1763.8
0100	96.0	85.0	63.8
0200	97.3	85.8	63.2
0300	97.5	85.8	61.7
0400	98.7	85.7	61.5
0500	99.3	87.2	60.7
0600	98.0	89.5	59.0
0700	96.3	91.2	57.7
0800	91.2	72.8	48.8
0900	87.7	64.3	50.7
1000	81.8	67.7	48.7
1100	79.5	61.7	46.3
1200	79.8	60.8	45.0
1300	77.2	63.7	43.3
1400	76.5	63.8	44.2
1500	81.7	65.2	40.8
1600	84.0	65.8	43.8
1700	85.7	71.8	48.5
1800	88.8	75.5	52.5
1900	87.5	73.5	54.5
2000	87.0	70.8	57.7
2100	82.7	64.3	57.8
2200	80.5	62.8	59.3
2300	83.2	64.7	57.8
2400	85.0	65.8	56.2
	Inches	Inches	Inches
Change	—.026	—.042	—.021
Rain	.02	0	0
Runoff	0	0	0
Percolation	.001	.001	0
Evapotranspiration	.076	.095	.066
Condensation-absorption	.031	.053	.045
ET-CA	.045	.042	.021

Percolation generally dwindled to a minimum or often stopped entirely in the latter part of the growing season. By this time evapotranspiration and percolation had depleted moisture in the large soil pores—the source of percolation water. Evapotranspiration was greatest in the warm summer month. Monthly evapotranspiration data can be compared with monthly air temperature and pan evaporation values for the same year (Table 3). Evaporation data are available only for the ice-free period.

Storage of soil moisture as evaluated in Table 2 usually decreases in the warm growing season and increases in the autumn, winter, and early spring

TABLE 2. — *Monthly summary of accretion, depletion, and storage of soil water on Lysimeter Y102C, 1949*

Month	Crop (1)	Accretion			Depletion				Storage 8-foot profile	
		Precipitation	Condensation Inches	Total	Runoff	Evapo-transpiration	Percolation	Total	Net increase	Net decrease
		Inches		Inches	Inches	Inches	Inches	Inches	Inches	Inches
Jan.	Meadow	5.54	1.19	6.73	0.01	1.75	0.14	1.90	4.83	—
Feb.	"	2.85	1.19	4.04	.01	2.09	1.35	3.45	.59	—
Mar.	"	3.89	1.34	5.23	.01	2.90	2.02	4.93	.30	—
April	"	2.93	.83	3.76	.01	4.02	.94	4.97	—	1.21
May	Corn	3.01	1.17	4.18	.06	4.07	.46	4.59	—	.41
June	"	3.40	.78	4.18	.05	5.19	.32	5.56	—	1.38
July	"	6.71	.33	7.04	.16	7.54	.18	7.88	—	.84
Aug.	"	2.68	.69	3.37	0	5.53	.06	5.59	—	2.22
Sept.	"	3.45	.90	4.35	.01	3.13	0	3.14	1.21	—
Oct.	Wheat	1.03	1.19	2.22	0	2.81	.01	2.82	—	.60
Nov.	"	1.55	.97	2.52	0	2.28	.02	2.30	.22	—
Dec.	"	2.94	1.19	4.13	0	1.96	0	1.96	2.17	—
Year		39.98	11.77	51.75	.32	43.27	5.50	49.09	9.32	6.66

(1) Meadow turned by spade May 6; corn planted May 9; corn harvested September 21; wheat planted October 3.

months. Some years there is a net increase for the year like that of 1949. Over a period of several years, however, the increases just about balance the decreases.

Condensation-Absorption

Well defined periods of weight increase during each day are converted to inches of water and tabulated as condensation-absorption (CA). It is possible that evapotranspiration (ET) from vegetation above the soil surface could have been occurring concurrently with CA at the surface. The resultant weight increase would not therefore show the entire value of CA. Actually then CA values obtained from lysimeter studies can be considered minimum values. True CA would probably exceed those presented here.

Although most of the CA evaporates after a few hours of sunshine, the data indicate that it has some soil-moisture conservation value. Without the CA or dew there would be more soil-moisture extraction by transpiration. This is substantiated by the work of Burgy and Pomeroy (1) who found that the evaporation of a given amount of intercepted moisture was accompanied by a like reduction in the amount of evapotranspiration from the plants.

The greatest monthly value of CA of 1.39 inches occurred in August 1951 on a corn lysimeter. Rainfall that month was only 0.75 inch. For 16 consecutive days the daily CA was 0.05 inches or greater, and one day, 0.08 inch. Although rainfall was greatly deficient then, there was no evidence of corn wilting.

Evapotranspiration

Well defined periods of weight decrease each day are evaluated and converted to inches of water and tabulated as evapotranspiration. In this process of nature, soil water is transferred into the atmosphere directly through evaporation from the soil or transmitted through the plant system to the leaf from which it is evaporated. In either case it is no longer weighed as part of the lysimeter.

Of all the water depletion factors evapotranspiration is the greatest. During the period of record it has averaged 80 to 90 per cent of the total depletion. In dry years this value reached 99.96 per cent. The runoff and percolation were very small.

Evapotranspiration (ET-CA) use of water has varied throughout the growing season according to the crop and the moisture supply, as shown in Table 4. ET-CA is the net loss of soil moisture and is commonly referred to as "consumptive use." In 1949, the corn lysimeter lost little moisture by ET-CA in May as its leaf area was quite small. In June also the leaf area was still developing. The increase in consumptive use was small. ET-CA in July however was the maximum for that year—7.21 inches. In August, ET-CA was lower mainly because less soil moisture was available for ET. Corn plants matured in September—thus the low ET-CA of 2.23 inches. In 1953, irrigation in July and August supplied ample moisture for consumptive use. Consequently, ET-CA in August then was as great as that in July.

A clear plastic sheet placed on the ground surface in June 1957 stopped evaporation from the soil surface. Transpiration from the corn plants, growing up through holes in the plastic, continued somewhat as usual. Values in Table 4, show transpiration for July to have been 4.14 inches and for August 2.40 inches. For the period of June 4 to September 9, during

which the soil surface was covered by plastic, the total transpiration was 8.35 inches. Evapotranspiration (ET-CA) for this period from the normal corn field, was calculated to be 15.01 inches. Evaporation would, therefore, have been 6.66 inches (15.01—8.35).

In general, water demand by corn was greatest in July and August. That for wheat was in May. Maturity of wheat plants in June reduced the water demand. After wheat harvest, the water needs of the young meadow seeded in March were not great.

TABLE 3. — *Average monthly air temperature and pan evaporation, 1949*

Month	Temperature	Pan evaporation (1)	evapotranspiration (2)
	°F	Inches	Inches
January	35.8	—	—
February	34.3	—	—
March	38.0	—	—
April	49.3	2.21	4.02
May	62.0	4.41	4.07
June	74.9	4.20	5.19
July	77.2	4.16	7.54
August	74.6	2.81	5.53
September	61.5	2.94	3.13
October	57.8	—	—
November	41.4	—	—
December	34.5	—	—

(1) Sunken pan, 6-foot diameter, 2 feet deep, water level at ground surface 2 inches below top rim of pan.
(2) Lysimeter Y102C, corn 1949.

TABLE 4. — *Monthly evapotranspiration (ET-CA) for corn, wheat, and meadow, growing season, Y102C lysimeter*

Crop	Year	April	May	June	July	August	September
		Inches	Inches	Inches	Inches	Inches	Inches
Corn	1949	—	2.90	4.41	7.21	4.84	2.23
	1953 (1)	—	3.28	3.26	6.79	6.75	3.45
	1957 (2)	—	—	—	4.14	2.40	—
Wheat	1950 (3)	1.19	5.62	4.11	3.11	3.93	3.53
Meadow	1955 (4)	3.53	6.60	4.92	6.17	5.79	3.02

(1) Irrigated in July with 2.93 inches and August with 2.90 inches of water.
(2) Transpiration alone; evaporation stopped by clear plastic sheet on ground surface.
(3) Wheat harvested July 7; new meadow cover thereafter.
(4) Hay cut and removed June 6, and July 22.

TABLE 5.—*Efficiency of water use, corn and meadow crops on lysimeter Y102C*

Crop	Year	Water used (1) (ET-CA)	Crop yield per acre	Weight of water used to produce 1 pound of crop	Crop produced by 1 inch of water
		Inches	Bushels	Bushels	Pounds
Corn	1941	17.4	80	394	4.6
	1945	18.9	34	586	1.8
	1949	21.5	144	334	6.7
	1953 (2)	23.5	196	273	8.3
	1957 (3)	13.2	125	151	9.5
			Tons		Ton
Meadow	1943	16.0	2.36	768	0.15
	1947	18.6	2.44	864	.13
	1951	20.4	2.70	856	.13
	1955	20.2	5.97	383	.30

(1) Water use period: Corn = May-September,
Meadow = May to date of last harvest.

(2)) Irrigated to prevent available moisture in 24 inch soil profile from depleting below 50 per cent.

(3) Evaporation from soil and infiltration of rainfall stopped June 6 to September 9, by plastic cover.

Established meadows used water at high rates in May (6.60 inches) and in July and August—about 6 inches each month. Harvest of the May crop early in June probably reduced its need of water for that month.

The crop yield and evapotranspiration (ET-CA) data from weighing lysimeters were combined to derive values on efficiency of water use (Table 5). In the three corn years of normal conditions, water use ranged from 17.4 to 21.5 inches. The greatest crop yield of 144 bushels per acre in this period corresponded with the highest value of total water use. This combination resulted in the maximum water-use efficiency—one inch of water producing 6.7 bushels of corn per acre. With irrigation in 1953, a 196-bushel crop yield was obtained on 23.5 inches of water. Efficiency increased to 8.3 bushels.

The plastic cover on the ground surface in 1957 prevented both evaporation loss and water absorption by infiltration from June 6 to September 9. Under these conditions and for the entire period May 1 to September 30, only 13.2 inches of water was used in producing 125 bushels of corn. Water-use efficiency was further increased to 9.5 bushels per inch of water used.

Percolation

Water that drains from the subsoil into the bedrock at the 5-foot depth and continues on through the 8-foot depth is collected in a tank, measured,

and sampled for chemical analysis. This percolation, or gravity water has varied from year and from crop to crop. Soil type also has had some effect.

On the Y101 series of lysimeters of sandstone rock and in shallow-rooted grasses, percolation has averaged 13 inches per year. Low values were about 6 inches per year and high values were up to 26 inches. An additional lysimeter at this site was seeded to deep-rooted alfalfabromegrass in 1947. For 5 years previous to this year, it was in shallow-rooted grasses and for 8 years after it was in deep-rooted vegetation. Its average percolation in the latter period was 8 inches per year or 5 inches less than that for those lysimeters continuously in shallow-rooted grass. In one 19-month period percolation was zero. Maximum annual percolation for the deep-rooted vegetation period was 13 inches. This crop transpired so much more soil moisture that on the average less was available for percolation.

Percolation from the crop-rotation lysimeters of Muskingum silt loam (well drained soil with shale bedrock, site Y102) has averaged 7 inches per year. Maximum values reached 17 inches and minimum values were less than 1 inch.

Percolation for the crop-rotation lysimeters of Keene silt loam (slowly-permeable soil with shale bedrock, site Y103) has averaged 7 inches per year. On two of these lysimeters crop yields were large because of higher fertilizer applications. Their percolation values have averaged slightly less than 7 inches, which is 1 inch per year lower than that from the two lysimeters of low fertility. The highest annual value was over 13 inches and the lowest less than 1 inch.

Percolation response to infiltrated rainfall varied largely because of differences in soil moisture at the time of the rain. For example, in March 1945 rainfall totaled 9.0 inches, runoff was 0.2 inch, and percolation from Y102C was 7.7 inches. Rain in September of the same year amounted to 9.7 inches, runoff was 2 inches, and the corresponding percolation was zero. In the first case, moisture in the soil profile on March 1 was about at its maximum. On September 1, the moisture content was at its minimum. On the latter date, there was 7 inches more storage space in the pores of the 0 to 40-inch profile than in the former.

From 1100 hour March 5, to 1200 hour March 6, rainfall totaled 2.6 inches. All this water was absorbed into the soil of lysimeter Y102C. Percolation rates increased noticeably by 2200 hour March 5, 11 hours after the rain started. At the end of the seventh day after the rain started, 2.7 inches of percolation had accumulated. Some of this percolation resulted from previous rainfall.

During this event, the maximum rates of percolation for a 3-hour period ranged between 0.07 and 0.12 inch per hour. As expected, these high rates occurred when most of the large soil pores, root channels, and other openings were used to transmit the gravitational water. This condition approached profile saturation under which condition percolation rates governed infiltration rates. Hydrograph analysis of runoff data showed that the minimum infiltration rate for a watershed of the same soil was about 0.08 inch per hour, a value not greatly different from the maximum percolation rate evaluated from the lysimeters.

Data on nutrient losses in percolates have been presented previously by the authors (3) and by Dreibelbis and McGuinness (2) and will not be repeated here.

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APPENDIX

Soil type description

Muskingum silt loam (sandstone origin). This soil type belongs to the Gray-Brown Podzolic group and is residual in origin. The entire profile is quite permeable and is classed as well-drained. It has a moderate fine crumb structure. A description of the profile near lysimeter site Y101 follows:

Depth (Inches)		
0— 8	—	Dark brown silt loam with texture approaching a loam.
8—16	—	Brown to yellowish-brown silt loam to loam with some sandstone fragments.
16—33	—	Brown to yellowish-brown loam with sandstone fragments.
33—51	—	Decomposed sandstone with sandstone fragments.
51—96	—	Slightly decomposed sandstone rock with few sandstone fragments.

Muskingum silt loam (shale origin). This soil type belongs to the Gray-Brown Podzolic group, is residual in origin, and occurs extensively in the North Appalachian Region. There is no mottling in the profile and it is classed as well-drained. It has a moderate fine crumb structure. A description of the profile located near lysimeter site Y102 follows:

Depth (Inches)		
0— 7	—	Brown to yellowish-brown, silt loam, plow layer.
7—14	—	Yellowish brown silt loam, slightly heavier than surface soil. Occasional shale fragments.
14—24	—	Yellowish brown silt loam to fine sandy loam containing frequent sandy shale fragments.
24—39	—	Partly decomposed shale in various stage of decomposition; fragments increasing in size with depth.
39—60	—	Layer of shale in various stages of decomposition containing layers of ferruginous material, mostly undecomposed.
60—96	—	Bedrock consisting of undecomposed shale with some shale in first stages of decomposition.

Keene silt loam. This soil type occurs extensively in the vicinity of the Research Station. It belongs to the same group of upland soils as the Muskingum series but differs distinctly from the latter in its hydrologic characteristics. The subsoil of the Keene silt loam is characterized by a

heavy, relatively, impermeable silty clay loam while the Muskingum silt loam subsoil is a rather pervious loam or silt loam. Because of the presence of a slowly permeable soil, it is classed as moderately well-drained. It has a moderate fine crumb structure. A description of the profile near lysimeter site Y103 follows:

Depth (Inches)		
0—7	—	Gray brown silt loam. Plow layer.
7—15	—	Yellowish brown silt loam, unmottled, slightly heavier than surface soil.
15—27	—	Yellowish brown silt loam to silty clay loam, slightly mottled with gray.
26—41	—	Mottled gray, yellowish, brown, and rust brown heavy silty clay, gray color predominating.
46—76	—	Gray heavy silty clay containing shale fragments.
76—96	—	Partially decomposed clay shale to decomposed clay shale.

THE SAN DIMAS DISTURBED SOIL LYSIMETERS

by J. D. SINCLAIR and J. H. PATRIC

SUMMARY.

This paper highlights some problems of establishing and operating lysimeters, and presents some preliminary results.

Twenty-six lysimeters installed in 1937 on the San Dimas Experimental Forest compare water losses and yields under several plants native to the chaparral-covered mountains of southern California. Local, uniformly mixed soil was placed in concrete tanks, 10—1/2 feet by 21 feet by 6 feet deep, each drained by a parallel top and bottom slope of 5 percent. Surface runoff and seepage are measured for each unit. Soil moisture is measured at uniform depths in several lysimeters with Colman electrical resistance units. A climatic station is on the site.

Soil settlement under a protective excelsior cover was completed by 1940. A six-year calibration period followed, when all but one lysimeter were seeded to grass. The soil in this unit has remained bare since 1940. Native shrubs and a species of pine were planted to replace the grass in 1946.

Compared to bare soil, all vegetation markedly decreased surface runoff and correspondingly increased infiltration. Evapotranspiration from vegetated soils was 2 to 3 times greater than from the bare lysimeter. Grass covered soils yielded most seepage.

Unconfined blocks of lysimeter soil have been managed the same as the conventional lysimeters to permit evaluation of the soil-air interface and root confinement effects on plant cover and rainfall disposition.

RÉSUMÉ.

Cette communication signale les problèmes de l'établissement et du fonctionnement des lysimètres, et présente quelques résultats préliminaires.

Vingt-six lysimètres, installés en 1937 dans la forêt d'Expérimentation de San Dimas, comparent les pertes et les rendements en eau sous une couverture de quelques espèces indigènes des montagnes de la Californie du Sud, couvertes d'une végétation connue sous le nom « Chaparral ». Du sol local, uniformement mélangé, a été placé dans des réservoirs (cuvettes) d'une largeur de 3 m 15, d'une longueur de 6 m 30, et d'une profondeur de 1 m 80; leur écoulement à été assuré par une disposition parallèle du fond et de la surface sous une pente de 5 pour cent. L'écoulement des eaux superficielles ainsi que des eaux infiltrées en profondeur dans le sol est mesuré séparément pour chaque unité. L'humidité de sol dans certains lysimètres est mesurée avec les unités de résistance électrique de Colman. Sur place, il y a un poste météorologique.

La colonisation du sol sous une couvertûre protectrice de laine de bois a été effectuée en 1940. Un calibrage d'une période de six ans a précédé l'ensemencement des lysimètres en graminées à l'exception d'un d'entre eux. Le sol dans ce dernier est resté nu dès 1940. Arbrisseaux indigènes ainsi qu'une espèce de pin ont été plantés en 1946 au remplacement des graminées.

Par rapport au sol nu, toute sorte de végétation a considérablement diminué l'écoulement des eaux superficielles et réciproquement a augmenté l'infiltration. L'évaporation et la transpiration des sols couverts de végétation étaient 2 à 3 fois plus grandes qu'au lysimètre à sol nu. Le sol couvert de graminées a produit la plus forte quantité d'eau de percolation (infiltration profonde).

Des blocs illimités de sol de lysimètres ont été traités de la même façon que les lysimètres typiques, afin de déterminer l'effet de restriction de l'écoulement des eaux dans ce fond ainsi que l'emprisonnement des racines sur la couverture végétale et la disposition des précipitations atmosphériques.

(1) Foresters, Pacific Southwest Forest and Range Experiment Station, Forest Service, U. S. Department of Agriculture.

Introduction

One of the world's largest lysimeter installations is in operation on the San Dimas Experimental Forest (2) in the San Gabriel Mountains, about 35 miles northeast of Los Angeles, California (Sinclair et al, 1953). The lysimeters were designed to compare the influence on rainfall disposition, of single plant species native to the local chaparral-covered mountains, and this paper highlights the problems in establishing and operating the San Dimas lysimeters and presents some preliminary results.

The lysimeter installation is one phase of a research program planned to reveal principles and develop practices of brushland management which will provide maximum yields of usuable water with minimum flood and erosions hazards.

The lysimeters were built between 1935 and 1937 by men and materials provided by the Civilian Conservation Corps and the Work Projects Administration. An installation of this kind, requiring much hand labor, could not have been undertaken without the assistance of these emergency programs.

Description Of The Lysimeters

The San Dimas lysimeters (Fig. 1) are the "filled" or "disturbed soil" type and thereby eliminate a source of experimental error unavoidable with natural soil blocks. The use of "in-place" lysimeters containing undisturbed blocks of natural soil was considered undesirable because of marked profile variations characteristic of the local mountain soils. The five kind of lysimeters at the San Dimas installation have been described previously (Colman and Hamilton, 1947). All are located within a deer- and rodent-proof enclosure in an area of relatively uniform topography and exposure at an elevation of 2,800 feet. On-site records are maintained of rainfall, air and soil temperature, relative humidity, wind movement, and evaporation for correlation of these climatic factors with evapotranspiration.

Large lysimeters

There are 26 large concrete lysimeters each $10^1/_2$ feet wide, 21 feet long and 6 feet deep (Fig. 2) arranged in a row 290 feet long. The group was constructed in 7 monolithic sections of 3 or 4 tanks each to minimize the danger of cracks developing in the installation. Each lysimeter holds approximately 64 tons, dry weight, of uniformly mixed soil. Each has a surface and bottom slope of 5 per cent on its long axis to provide drainage. All concrete surfaces in contact with the soil were coated with a waterproof phenolic resin paint to minimize reaction between the concrete and soil or plant roots.

Recesses in the interior surfaces of all walls were intended to reduce the downward movement of water between the wall and soil block, especially when the soil is dry and has shrunken away from the wall. This feature has not prevented the occurrence of some "false" seepage caused by water movement around rather than through the dry soil block during the first rains of the winter season. At times, some soil has been carried down with the water, causing cave-ins around the edges of the soil block. These holes have been filled with lysimeter stock soil, a supply of which was stored for replacement needs and other purposes.

(2) A field unit of the Pacific Southwest Forest and Range Experiment Station maintained in cooperation with the State of California, Department of Natural Resources, Division of Forestry.

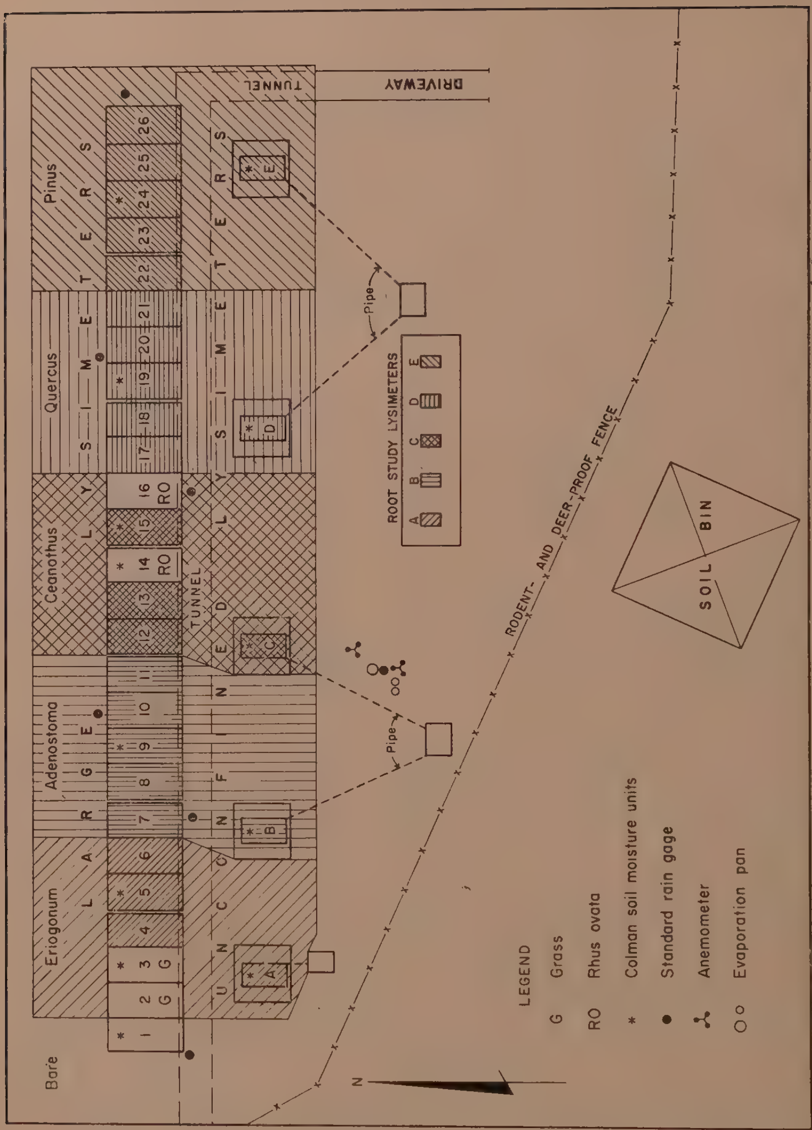

Figure 1 — The San Dimas lysimeter installation

DIAGRAM OF A SINGLE LARGE LYSIMETER
SURFACE AREA 5-MILACRES (10½ X 21 FEET)

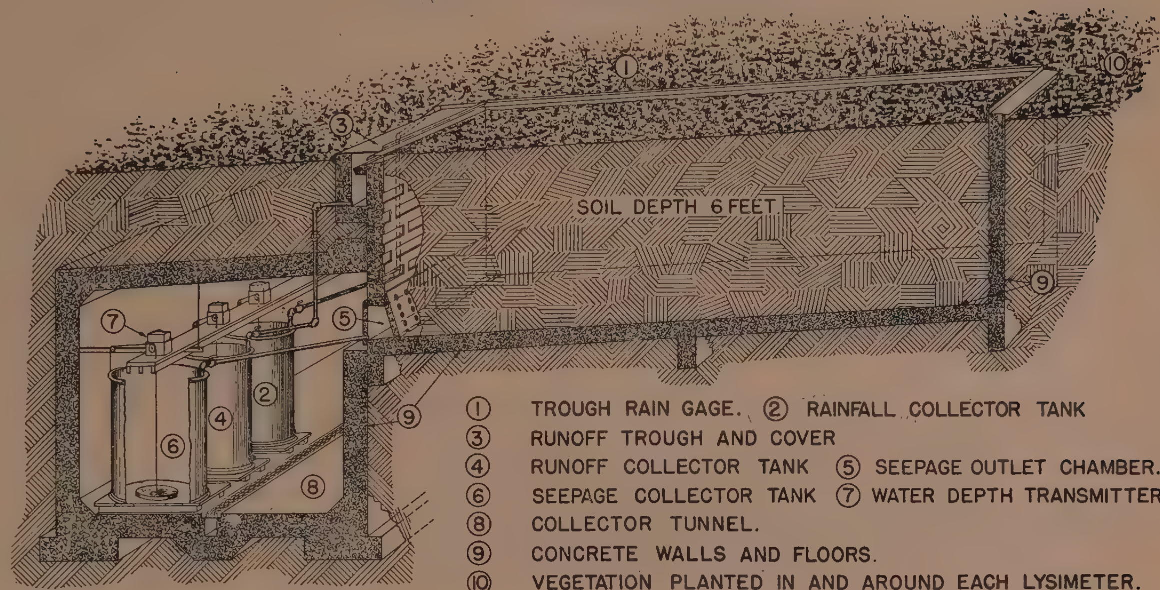

Figure 2

The walls between lysimeters are covered by metal troughs 6 inches wide and 2 inches deep designed to carry off rain falling on the walls and to provide measurements of rain falling through the crowns of the vegetation. Some rain was found to splash from these shallow troughs during intense storms. Although this was corrected by increasing the trough depth to 6 inches, measurements of throughfall have not been carried forward. Rainfall interception by the vegetation, and both throughfall and stemflow, have been included in calculations of total evapotranspiration.

Runoff from each lysimeter is caught in a trough extending across the lower end of the tank at the soil surface. Seepage from each soil block drains through a perforated concrete plate placed across the lysimeter bottom at its lower end. Runoff and seepage from each lysimeter are measured separately in collector tanks located in a tunnel adjacent and parallel to the row of lysimeters. Separate tanks also are provided to measure rainfall or throughfall. Some of the collector tanks are equipped with water-stage transmitters (Colman and Hamilton, 1944) which are connected electrically with strip charts to record rates of runoff and seepage.

Gravimetric soil-moisture sampling was carried on periodically in two of the large lysimeters for several years to provide direct measurements of water loss by evapotranspiration. Sampling was not extended to other lysimeters because of the labor required and the possible effects of this soil disturbance on lysimeter characteristics. The need for additional soil-moisture measurements and a method to obtain them in situ led to the development of an electrical moisture indicating instrument (Colman and Hendrix, 1949). By 1952 these instruments had been installed in the bare lysimeter and in one representing each plant species.

Unconfined Lysimeters

The effects of the soil/air interface in preventing free drainage and causing abnormal soil moisture conditions in conventional lysimeters were recognized when the San Dimas installation was planned. Therefore, unconfined lysimeters were designed to aid in evaluating effects of the artificial environment in the large lysimeters on soil moisture, plant development, and on the disposition of rainfall. Unconfined lysimeters also serve as a transition between conditions in the large lysimeters and in the field.

Five separate unconfined lysimeters were installed near the large lysimeters. Pits were dug 17-1/2 feet square and 7 feet deep and refilled with the same mixed soil used to fill the large lysimeters. A plot 7-1/2 feet wide and 14-1/2 feet long with surface gradient of 5 per cent was laid out on each refilled soil surface. The sides and upper end of the plots were bounded by sheet-metal strips 12 inches wide half-buried in the soil. Runoff is caught in a trough at the lower end of each plot and is collected in tanks. Each tank is equipped with a water-stage transmitter to provide measurements of runoff rates on a strip-chart recorder. The unconfined lysimeters are considered to be soil blocks 6 feet deep surrounded on sides and bottom by the same kind of soil, thus providing unobstructed movement of moisture from the soil block. Offsetting this advantage is the fact that seepage cannot be measured but must be calculated from records of soil moisture. These data were obtained by gravimetric methods in earlier years as in the large lysimeters. By 1952 Colman electrical instruments were installed in all of the unconfined soil blocks and through the soil beneath them to bed rock.

The Lysimeter Soil

The San Dimas lysimeters were filled with reddish sandy clay-loam soil developed residually at the site from dioritic rock. In situ the soil showed little tendency toward profile development, so no attempt was made to segregate surface from subsurface layers when the lysimeter soil was excavated. About 2,800 cubic yards of soil was taken from the top six feet of the lysimeter excavation. The soil was mixed thoroughly, passed air-dry through a $^3/_4$-inch screen to remove large rocks, remixed and stored to keep it dry. Analysis of random samples of the stored soil showed no significant differences in texture, the average content being 60 per cent sand, 25 per cent silt, and 15 per cent clay. Further tests showed the wilting point of the soil to be 7 per cent and its field capacity about 18 per cent moisture content.

The soil was placed in the large lysimeters and in the unconfined lysimeters pits in layers 3 inches deep. Each layer was "chopped" through with flat-bladed spades. Prior tests had shown that this method maintained uniform density and other characteristics of the mixed soil. At the time of filling, the range in density of the soil in the large and unconfined lysimeters was less than 2 per cent. As a result of these tests, the soil in both was considered to be physically similar.

The large and unconfined lysimeters were over-filled 12 inches to allow for soil settling when exposed to weather under a mulch of excelsior. This extra depth of soil was held in place with temporary wooden walls. Surveys of the soil surfaces were made annually for three years. By 1940, the third year after exposure, soil settling had become negligible. Total settling averaged about 6 inches, of which 70 per cent had taken place during the first year. The remaining over-fill was removed in the fall of 1940. At that time the average dry weight of soil in the large lysimeters was approximately 127,000 pounds and that in the unconfined lysimeter pits 206,000 pounds. Three years settling had increased soil density 8.3 per cent — to 1.57 grams per cubic centimeter in the large lysimeters and 1.55 grams per cubic centimeter in the unconfined units.

Periods Of Operation

The research program for the large and unconfined lysimeters has included three periods of operation. During the first period, 1937—1940, soil settlement was the principal objective. All of the lysimeters were maintained without vegetation, but the soil was covered with excelsior to prevent excessive erosion. Rainfall, runoff, and seepage were measured during this period to detect inconsistencies in the performance of individual units.

The second, or grass-cover, period (1940—1946) was started after the surplus soil had been removed. *Bromus mollis*, an annual grass, was seeded in all but one of the large lysimeters, in all of the unconfined units, and in buffer areas surrounding both groups. These buffer areas were planted to minimize border effects in the lysimeters. Thus the vegetation in each lysimeter is a sample of that on a larger area.

Reasons for the establishment of a grass cover were: (1) to compare the performance of the lysimeters and detect consistent or erratic differences between units under similar vegetation, (2) to create soil structure by growing plants in the artificially mixed and placed lysimeter soil, and (3) to obtain information concerning the water economy of this annual grass. After the

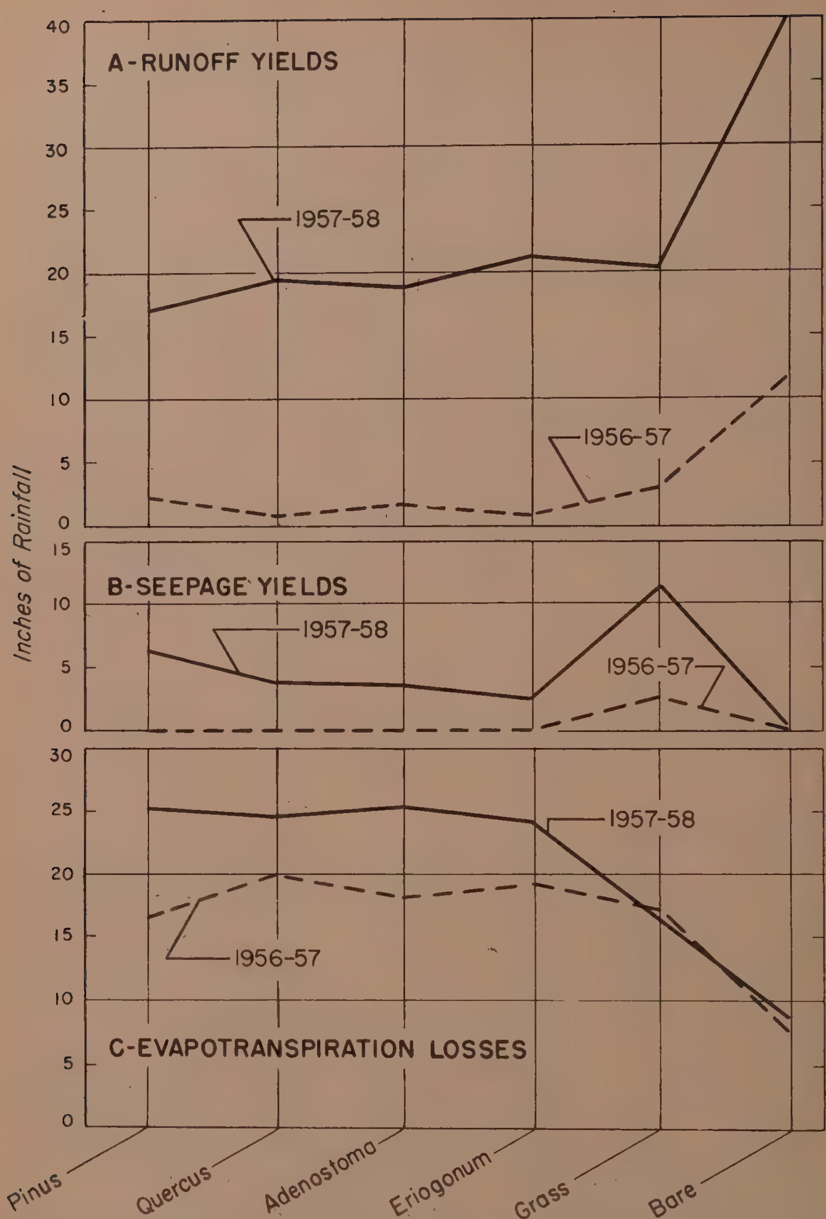

Figure 3 — Influence of plant species on rainfall disposition in the San Dimas large lysimeters.

first seeding, the grass was allowed to reseed naturally in both the lysimeters and border areas.

The soil in one of the large lysimeters has been maintained bare since the removal of the overfill. During the grass-cover period this bare soil lost much fine material from its surface and developed a hard crust. In contrast, erosion was negligible on grass-covered soil. In the rainy season of 1940—41, infiltration into all lysimeters newly seeded with grass remained at the low value (less than 10 inches per year), characteristic of the unvegetated overfill period. Entry of water into grass-covered soils markedly increased during subsequent years, while infiltration into the bare soil remained low and relatively constant.

The third, or current, period started in 1946 when the grass cover was replaced by four shrubs and a species of pine, all native to the mountains of southern California. The initial species selected for this test of comparative water economy were: *Eriogonum fasciculatum, Adenostoma fasciculatum, Ceanothus crassifolius, Quercus dumosa and Pinus coulteri.* Blocks of each species occupy five contiguous large lysimeters, one unconfined lysimeter and adjacent border areas. The large lysimeter kept bare during the previous period has been maintained in that condition.

Two changes have been made in the large lysimeter plantings since 1946. First, interest in the water economy of grass in relation of other kinds of vegetation led in 1951 to replacing *Eriogonum* in two of the lysimeters with a mixture of native bunchgrasses. Second, because several *Ceanothus* plants died, the species was replaced with *Rhus ovata* in two lysimeters during 1952.

Preliminary Results

Large Lysimeters

The influence of several plant species on rainfall disposition in wet and dry years is shown by data obtained from the large lysimeters during two recent years (Fig. 3). Rainfall of 20.3 inches during the winter 1956—57 produced responses typical of the 4 preceding drought years when rainfall each winter was below the annual average of 27.6 inches. A near record 48.4 inches of rain fell during the winter of 1957—58. In these years of low and high rainfall, vegetation always profoundly influenced soil-moisture regimes within the lysimeters.

Runoff yields from tree-, brush-, and grass-covered soil varied from 0.7 to 3.0 inches depth during 1956—57 and from 15.9 to 20.8 inches during 1957—58 (Fig. 3-A). Comparable runoff yields from the bare soils were very much higher, amounting to 11.6 inches in 1956—57 and 39.1 inches in 1957—58. Infiltration, computed by substracting runoff from rainfall, was correspondingly much lower in the bare soil than in soil covered with vegetation.

During 1956—57, as in the preceding dry years, no sub-surface water seeped from the bare lysimeter or from those covered with woody plants. The grass lysimeters, however, produced seepage each year—2.5 inches in 1956—57 (Fig. 3-B). Even in winters of low rainfall, the grass-covered soil soon was wet to field capacity because grass used little, if any, moisture stored below depths of about 4 feet in the large lysimeters. The heavy rains of 1957—58 produced seepage from all of the lysimeters, the greatest yield being from grass. Even the bare soil yielded a trace of sub-surface flow for the first time since 1951—52.

Evapotranspiration losses from the tree- and shrub-covered lysimeters were greatest in 1957—58 and varied least by species that year, when most water was available (Fig. 3-C). During both 1956—57 and 1957—58 evaporation from the bare soil and evapotranspiration from the grass-covered units varied little from the annual averages of 8.6 inches and 16.5 inches respectively. Even during dry years soil moisture remained high in the lower depths of these lysimeters. In contrast, soil-moisture measurements since 1952 in the tree- and shrub-covered lysimeters have shown that the soil was dried to the wilting point each year before the onset of the rainy season.

Relations between large and unconfined lysimeters

There are evident differences between the growth of woody plants in the large lysimeters and in unconfined blocks of lysimeter soil. The height

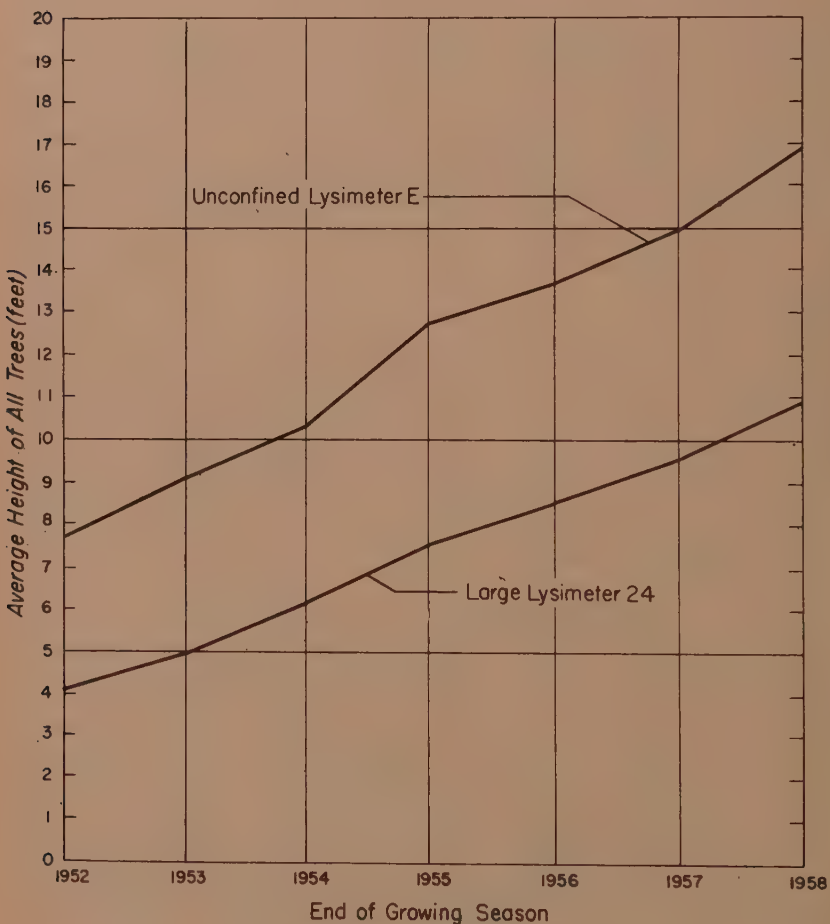

Figure 4 — Average annual height growth of *Pinus coulteri*.

growth of *Pinus coulteri* in a large lysimeter compared to that in an unconfined lysimeter is an index of this difference in plant development (Fig. 4). The faster growing trees in the unconfined soil have over 4 times the stem volume of those in confined soil. This growth variation of similar trees in an environment differing only in soil confinement may be attributed to: (1) restriction of roots in the large lysimeter, and (2) abnormal soil moisture conditions in this lysimeter. These moisture conditions are known to be caused by the soil-over-air seepage interface phenomenon, its effects on free soil drainage, and in turn on soil aeration (Kittredge, 1940, 1941). Colman (1946) has proposed a method of removing the abnormal moisture in the San Dimas lysimeters by improving soil drainage under controlled moisture tension. To date the installation of equipment required has not been feasible. Detailed analysis of data will be required to evaluate the unnatural conditions and their influence upon rainfall disposition in the large lysimeters in relation to rainfall disposition in the unconfined lysimeters.

Experience with the San Dimas lysimeters has demonstrated some of the inherent problems in their use, especially for hydrologic studies involving deep-rooted plants. For this reason caution must be exercised in interpreting and using data obtained from instruments of this type.

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THE INFLUENCE OF A STAND OF PINUS COULTERI ON THE SOIL MOISTURE REGIME OF A LARGE SAN DIMAS LYSIMETER IN SOUTHERN CALIFORNIA

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SUMMARY

A comparison was made between the soil moisture regimes of a lysimeter growing *Pinus coulteri* and a lysimeter that was barren. The quantity of soil moisture (Qsm) during drying periods was described by the equation $Qsm = Qsm_0 \cdot e^{-kt}$; with $k = 0.0097$ for *Pinus coulteri* and 0.0069 for barren. (Qsm_0 = initial soil moisture; t = time of drying; k = loss rate constant). The loss rates were nearly the same at various soil depths under *Pinus coulteri*, but they diminished with depth under the bare surface. The zone of maximum moisture loss descended in the soil under the pine stand 1.9 cm. per day until the entire 1.83 meter soil depth was dry; whereas it remained near the surface in the bare soil.

RÉSUMÉ

Cette étude compare l'humidité du sol dans un lysimètre où l'on a cultivé *Pinus coulteri* et un lysimètre entièrement nu.

On peut exprimer la teneur en eau du sol (Qsm) pendant les périodes de sécheresse par l'équation

$$Qsm = Qsm_0 \cdot e^{-kt}$$

avec $k = 0.0097$ pour *Pinus coulteri* et 0.0069 pour le sol nu. Les constantes étaient la même à des profondeurs différentes sous les *Pinus coulteri*, mais elles diminuent avec la profondeur sous la surface nue. La zone de la plus grande diminution de l'humidité descend dans le sol sous un couvert de pins, 19 mm chaque jour jusqu'à ce que le sol à la profondeur de 183 cm était sec; par contre, cette zone se localisait auprès de la surface du sol nu.

INTRODUCTION

Moisture stored in the soil from winter precipitation is the only source of water for the forest growing in areas of summer drought as in California. The rate at which this moisture is used and the portion of the soil profile from which the use is taking place at any time are items of interest to the forester. This paper will describe the soil moisture losses as they occur from certain of the San Dimas lysimeters. These lysimeters contain homogeneous blocks of soil 20.8 feet × 10.5 feet × 6 feet deep, with a surface area of 5/1000 acre or approximately 20 square meters. The soil is a sandy clay loam with a wilting point moisture content of seven per cent, and a field capacity moisture content of eighteen per cent. The soils in the lysimeters were packed to a bulk density of 1.56 gms. per cc. Moisture content is periodically measured by using Colman electrical fiberglass soil moisture units placed at depths of 3", 6", 12", 18", 24", 30", 42", 54", and 66" in each lysimeter. The analysis of soil moisture loss reported in this paper was made from the data obtained from these units.

The vegetation on the lysimeter being studied was *Pinus coulteri*, and comparison was made with a lysimeter maintained barren of vegetation. The pine cover was established in February of 1946 using one year old stock. As of the latest data used in this paper the plantation trees were 12 years old. The basal area of the stand in 1956 was 0.0418 m². There were 19 trees, about 4 meters in height, on the lysimeter.

The climate during the first decade of growth of this stand has been such that from 1946 to 1956 there was a total of 554 cm. (218.2") of precipitation. During this period there was an average annual evaporation of 159 cm. (62.73") from a standard 1.03 meter diameter evaporation pan. The water balances for the two lysimeter tanks are shown in Table One. Annually an average of 17.5 cm. (6.89") of the precipitation ran off of the surface of the pine covered lysimeter and 35.0 cm. (13.78") ran off of the barren lysimeter. There are thus obvious differences in the quantity of water entering the soil of the two lysimeters. Seepage occurred from the pine covered lysimeter only 5 times during the ten year period, and only twice from the barren lysimeter. The yearly climatic regime is characterized by a period free of precipitation during the summer which ranges from one month to six months in duration. Table Two shows the monthly precipitation for a two year period including both a high precipitation year and a low precipitation year. The summer drought period for both years except for light rains was generally of the duration of six months. The lysimeters because of this long summer drought period allow the study of the complete drying of soil moisture under the various vegetation types present.

Soil Moisture Regime of the Lysimeters

The moisture regime of the lysimeter vegetated with *Pinus coulteri* was usually characterized by the soil being wetted to field capacity or above during the winter rainfall period, and dried to the wilting point of the soil during the summer drought period. The depth to which the soil

TABLE 1 — Water balance of the bare and *Pinus coulteri* covered lysimeters for the decade 1946—1956 (inches of water).

Year (1)	Precipitation	Runoff		Infiltration	
		barren	pine	barren	pine
1946—1947	27.53	19.79	9.86	7.74	17.67
1947—1948	16.06	9.51	7.23	6.55	8.83
1948—1949	17.09	6.85	2.56	10.24	14.53
1949—1950	21.05	13.36	6.32	7.69	14.73
1950—1951	11.55	4.99	2.23	6.56	9.32
1951—1952	42.17	31.50	18.15	10.67	24.02
1952—1953	16.01	8.41	3.64	7.60	12.37
1953—1954	25.39	18.48	10.69	6.91	14.70
1954—1955	20.44	11.94	3.33	8.50	17.11
1955—1956	20.89	12.99	4.93	7.90	15.96
Average					
Inches	21.82	13.78	6.89	8.04	14.92
Cm.	55.42	35.00	17.50	20.42	37.90

(1) Hydrologic year October 1—September 30.

TABLE 2 — Yearly regimes of precipitation and evaporation for two consecutive years at the San Dimas lysimeters.

Month	Precipitation Inches		Evaporation Inches	
	1951—1952	1952—1953	1951—1952	1952—1953
October	1.82	0.00	6.10	5.87
November	2.66	4.65	2.93	2.19
December	11.29	4.70	1.86	1.43
January	12.41	1.62	1.46	2.41
February	1.98	1.36	2.47	3.16
March	8.28	1.49	2.56	3.51
April	3.19	1.80	3.39	3.45
May	0.00	0.21	6.79	5.53
June	0.00	0.08	5.93	6.54
July	0.00	0.00	9.00	10.29
August	0.00	0.07	8.68	9.32
September	0.54	0.00	6.65	7.76
Annual				
Inches	42.17	16.01	57.52	61.46
Cms.	107.11	40.66	146.10	156.11

was wet during the winter rainfall period was a function of the amount of rainfall that occured. During years of heavy rainfall, the soil was wet completely. The soil moisture regime during two hydrologic years is shown in figure one. The even pattern of soil moisture withdrawal as a function of depth is particularly striking, and the long period of soil drought is apparent. At the one meter depth in the soil drought conditions may prevail for more than a year, although the roots of the Coulter pine are growing in this zone as well as in the surface layers of the lysimeter soil. The roots dried the entire soil column to a depth of six feet and the drying occurred as an advancing front into the soil. Thus the subsoil did not dry out until the upper layers of the soil were dried. The following year not enough rainfall occurred to wet the entire soil column and the intermittent quality of the storms allowed considerable soil moisture to be lost even in the middle of winter.

The soil moisture regime under the bare lysimeter (figure one) affords a contrast in that the soil rarely dried much below a depth of 30", even in the longest drought. Soil conditions were damp in contrast to the droughtiness of the subsoil of the pine cover. The soil moisture use during the winter dry periods did not extend as deep in the bare soil as in the pine covered soil. Thus in the month of February, the soil dried rapidly under the pine to a depth of 66 cm., but under a barren soil surface the drying advanced only to a depth of approximately 15 cm. During the summer dry period the soil under the pine was dried throughout the 183 cm. depth whereas the barren soil was similarly dried only to depths of 25 cm. These conditions could be considered to simulate those found in a forest contrasting vegetated areas and root free bare openings. The forester by his manipulation of the vegetation can thus achieve effects between one or the other of these two extremes.

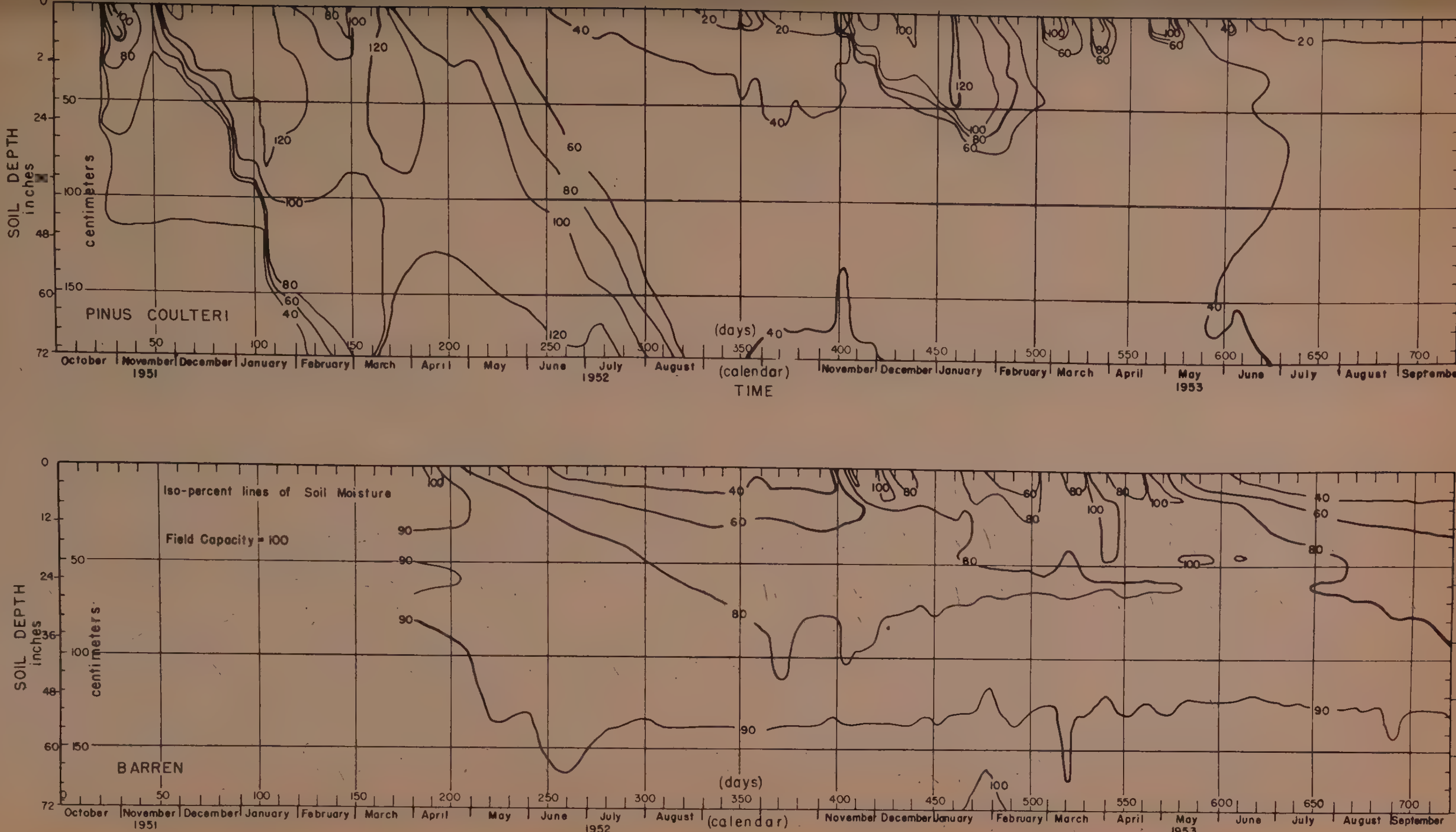

Fig. 1 The soil moisture regime of the barren lysimeter and the lysimeter with *Pinus coulteri*. Field capacity moisture content of the soil is 28 % by volume.

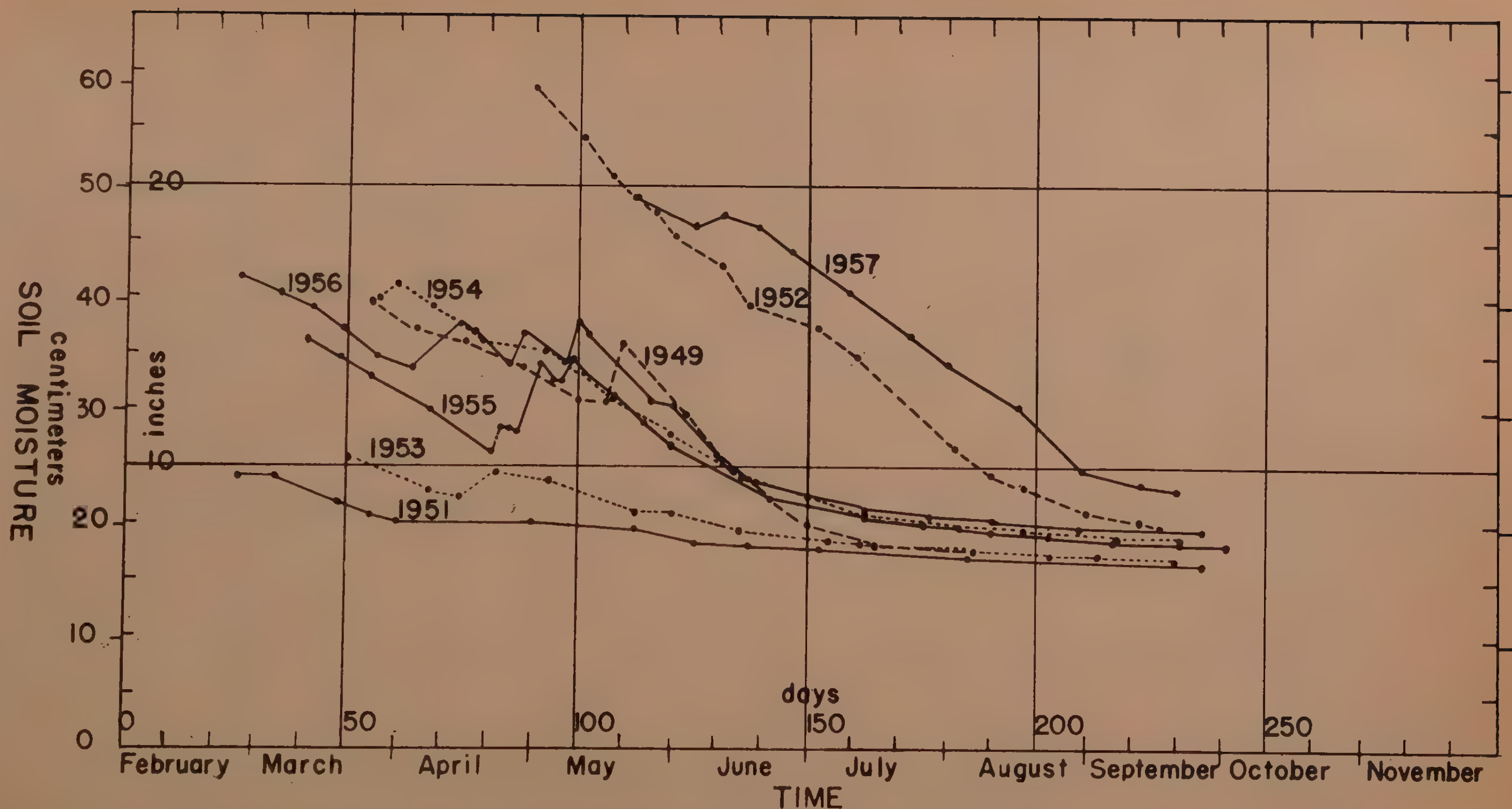

Fig. 2 Depletion curves for total soil moisture content of the lysimeter with *Pinus coulteri*.

Soil moisture depletion for the entire soil mass in the lysimeters as a function of time indicates that the summer drying of the soil proceeds in a similar rate pattern each year (figure two). A variation each year, however, is the date of initiation of the drying season or last rainfall. When all of the dates are adjusted to the same initial conditions of soil moisture and occurrence of last large storm of the season the soil moisture depletion curves as a function of time appear as in figure three. These data suggest that there is decreasing rate of soil moisture depletion with time. Total soil moisture storage (Qsm) can thus be related to the initial soil moisture storage or field capacity (Qsm_0) and time (t) as in figure four by the following equation:

$$Qsm = Qsm_0 \cdot e^{-kt}$$

The rate constant k varied from 0.0085 in 1957 to 0.0142 in 1949, with most of the years closely represented by a rate constant of 0.0097. These relationships seem to have held from the beginning of the life of the pine stand.

In contrast the lysimeter maintained barren of vegetation (figure five) had a lower rate of loss of soil moisture which if described as a linear function of time would be 0.02" per day, or $Qsm \doteq -0.02\ t + Qm_0$ where Qsm = total soil moisture in the soil profile (inches depth) and Qm_0 = soil moisture at time that drying began. The data are also well described by the function used above for the pine covered lysimeter, the soil moisture

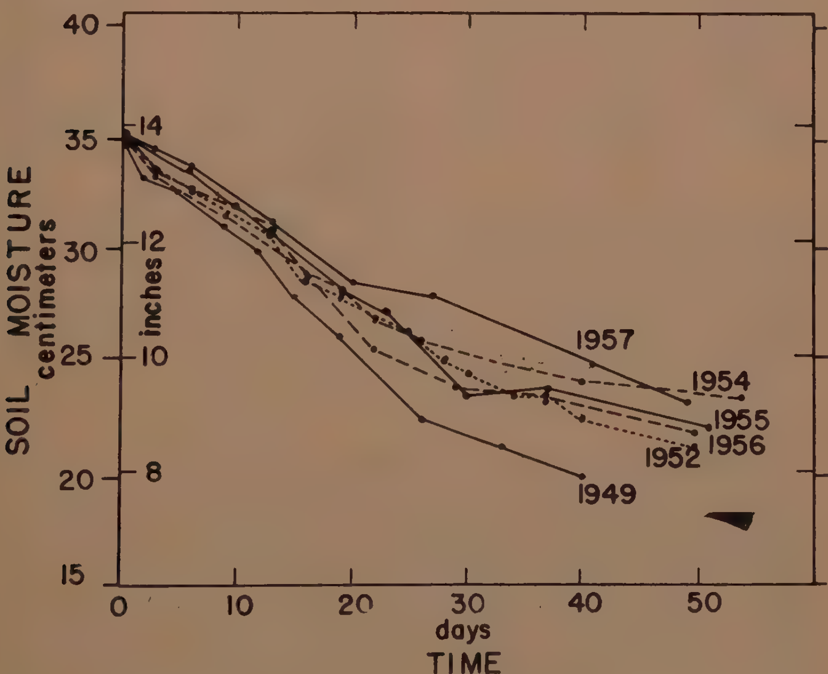

Fig. 3 Comparable portions of depletion curves for total soil moisture content of *Pinus coulteri* lysimeter adjusted to the same initial time.

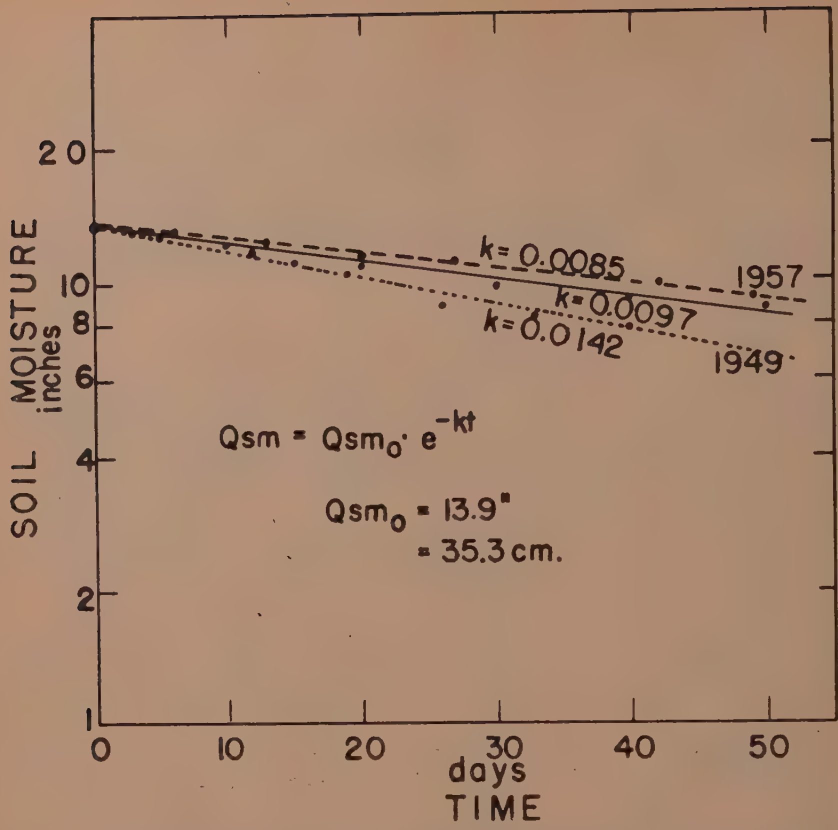

Fig. 4 The equation and loss rate constants describing comparable portions of soil moisture depletion curves for two extreme years and an average curve.

loss in the barren lysimeter had a rate constant of .0069. The equation describing the loss is:

$$Qsm = Qsm_0 \cdot e^{-.0069\,t}$$

Soil moisture depletion from various soil depths

The soil moisture depletion of various depth horizons of the lysimeters takes place as a succession of removal of layers of soil moisture, the removal of the uppermost layer occurring first. The appearance of the moisture depletion curves at various soil depths during the drying period in 1952 under the *Pinus coulteri* cover is shown in figure six. Each soil layer is successively drained, beginning with the uppermost and after the dessication of that layer has reached a certain point, the next lower layer begins to lose moisture. For the homogeneous soils of the lysimeter tank the rate of loss from each horizon is nearly the same, indicating that possibly the loss rate is a function of a property of the soil such as permeability. The moisture

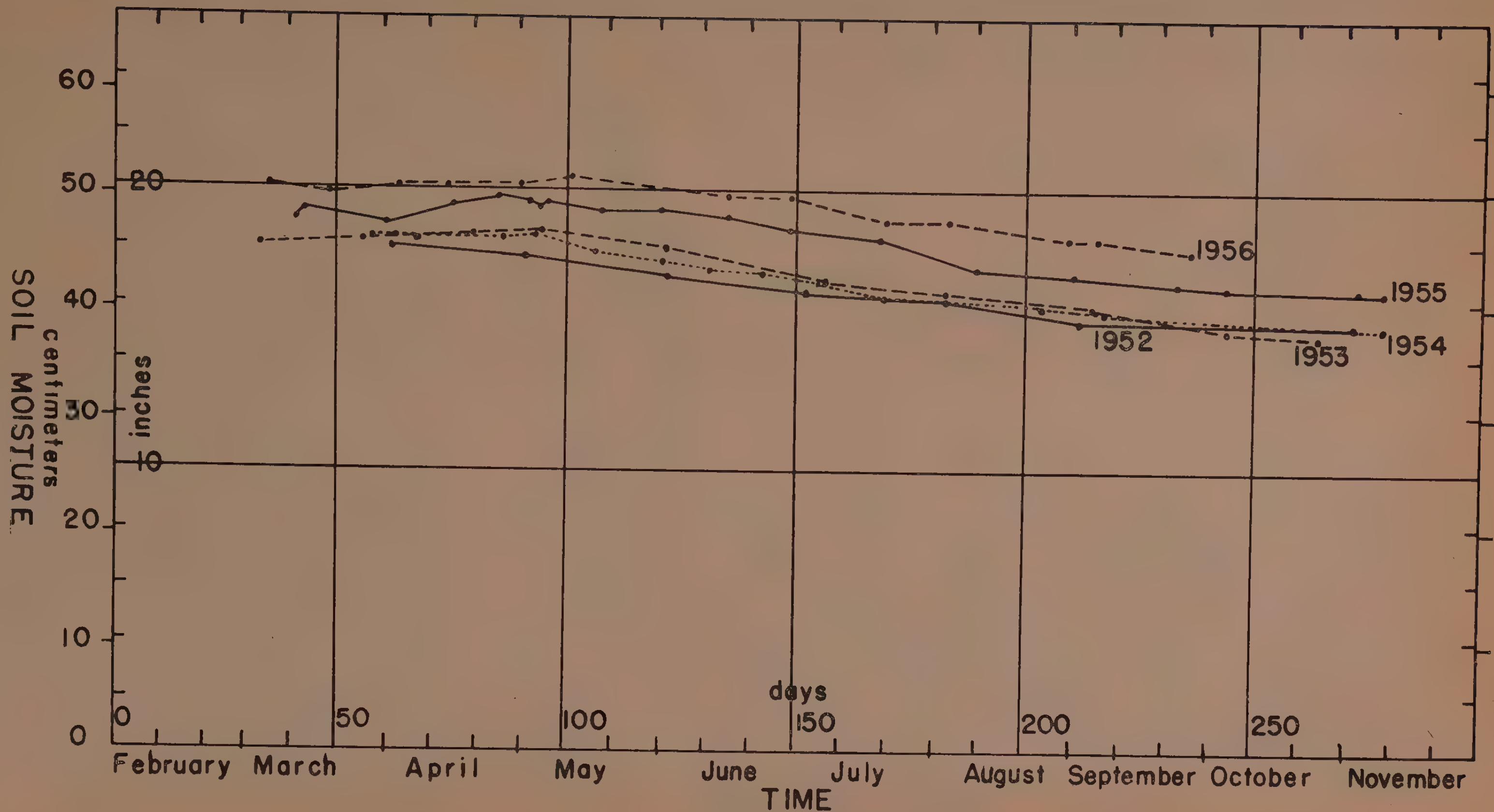

Fig. 5 Depletion curves for total soil moisture content of the barren lysimeter.

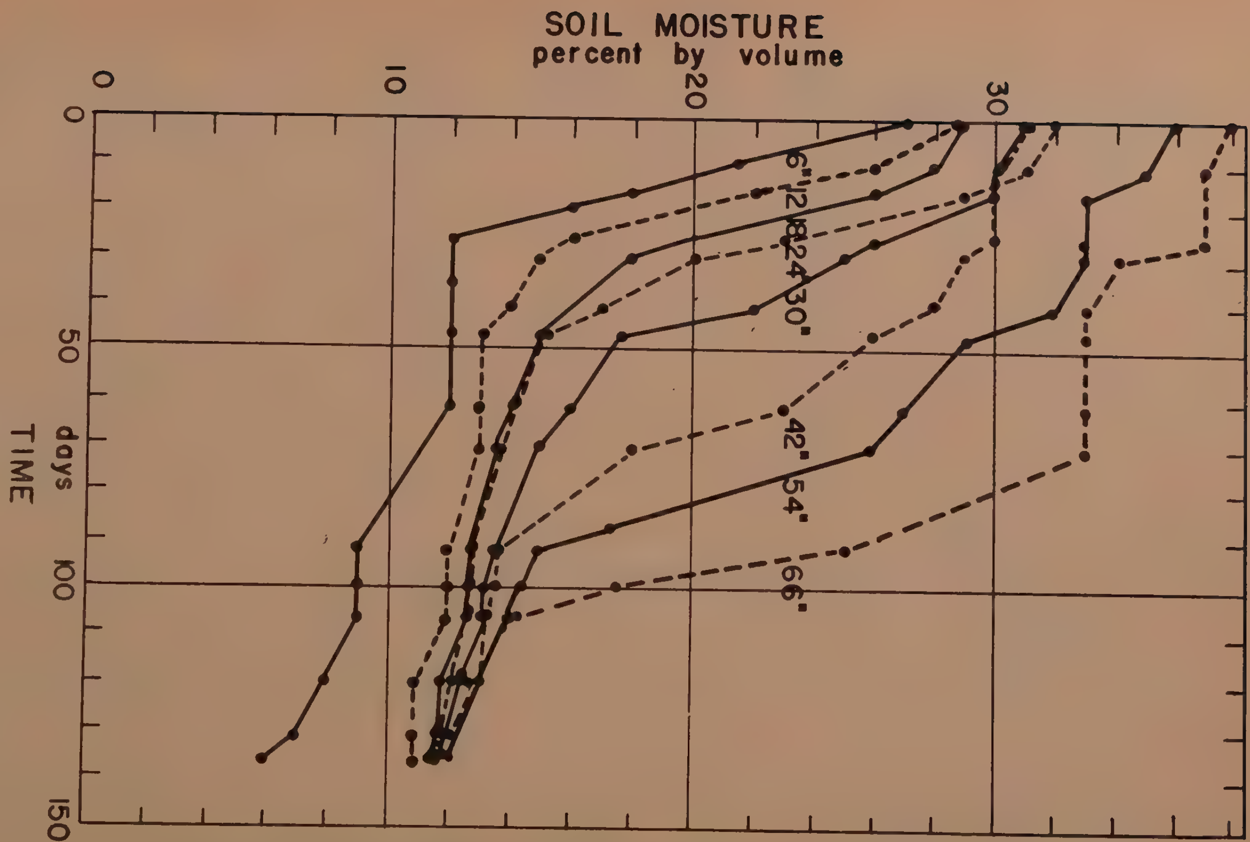

Fig. 6 Lysimeter soil moisture depletion at various soil depths under *Pinus coulteri* beginning Mai 1, 1952.

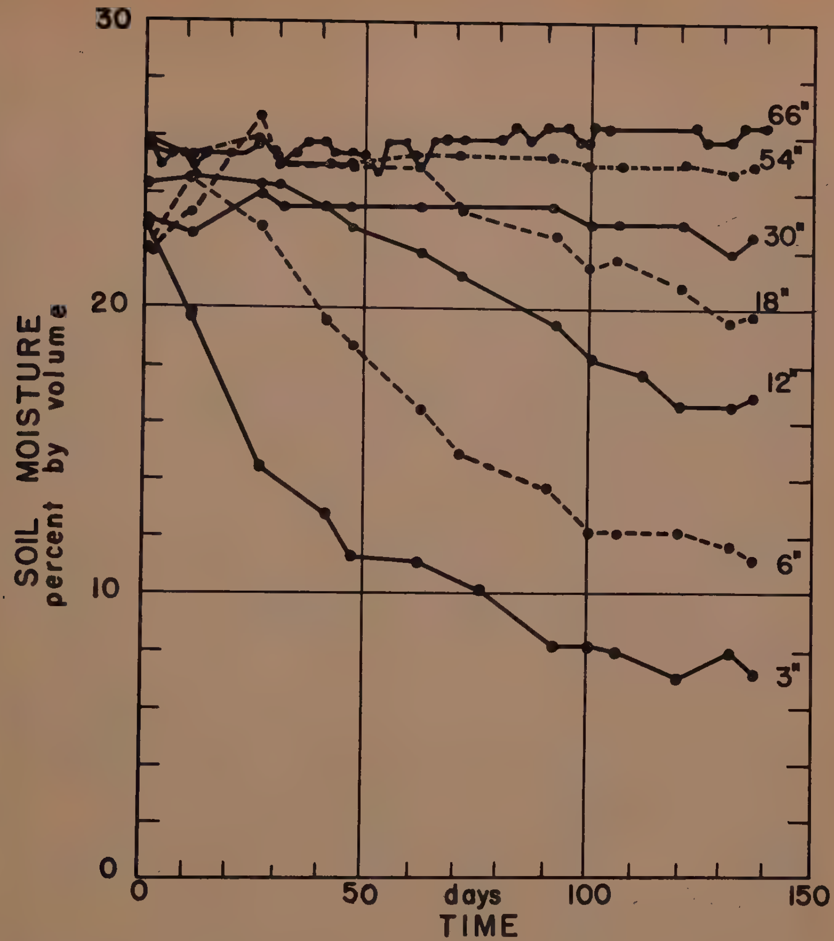

Fig. 7 Soil moisture depletion at various soil depths in the barren lysimeter beginning May 1, 1952.

depletion rate remains nearly steady with increasing depth increments of the soil, being approximately .005" of water per inch depth of soil during the peak drying period of that layer. The bare soil (figure seven) dries in response to an entirely different regime, the top soil layer drying fastest, and each successive depth increment of the soil drying at a lesser drying rate, until finally the rate is essentially zero for the soil at 54" and 60". The general equations which describe the drying of each successive depth increment of the bare soil are all of the form $Qsm = Qsm_0 \cdot e^{-kt}$. As is seen in figure eight, the beginning of the drying period described by this equation is successively later with depth, being time zero at 3", 11 days at 6", 30 days at 12", 62 days at 18", and 92 days at 30". The respective loss rate constants which apply for each of these depths once drying begins are:

3"	.0078 (.0148 during first 20 days)
6"	.0066
12"	.0039
18"	.0032
30"	.0024
54" & 66"	Zero

The 3" layer of the soil during the first 20 days had a loss rate constant of nearly double that which typifies the layer during the next 100 days of drying. This is attributed to moisture loss to the layer immediately below and to the atmosphere.

The loss rate of soil moisture as related to soil depth for dates during the drying season is shown in figure nine, for both the barren and Coulter pine covered lysimeter. In the barren lysimeter the maximum rate of loss of soil moisture is always near the soil surface whereas in the pine lysimeter the maximum rate of loss occurs at successively deeper soil layers as the season advances until the bottom layer is reached at the end of the drying period. The rate of penetration of this zone of maximum drying by the pine stand was approximately 1.9 cm. ($^3/_4$") per day. The observations perhaps represent the ideal field case since the soil is homogeneous.

Evaporation tank measurements and lysimeter moisture loss

The relationship which might exist between the loss of moisture from the lysimeter and external climatic variables is of particular interest. The lysi-

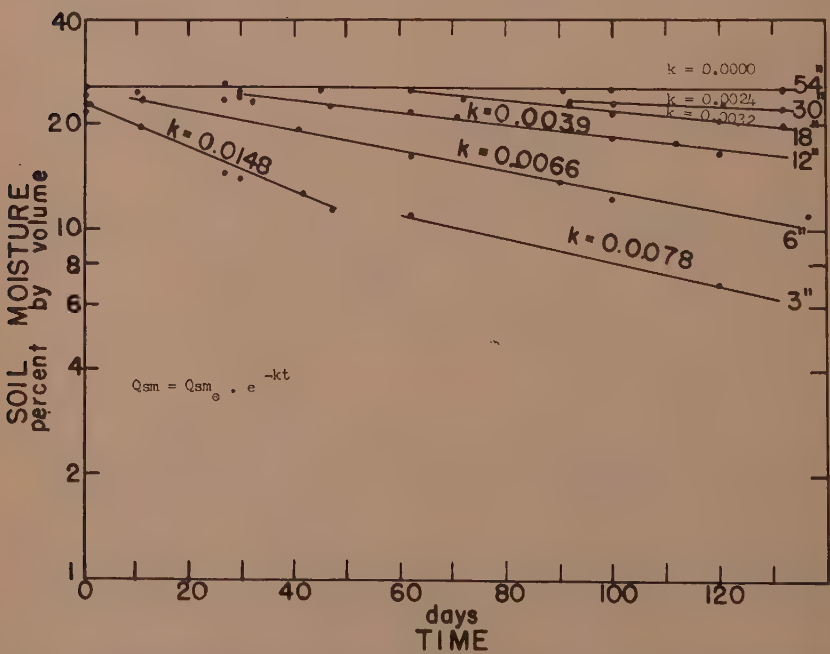

Fig. 8 The equation and loss rate constants for soil moisture depletion at various soil depths in the barren lysimeter for the period beginning May 1, 1952.

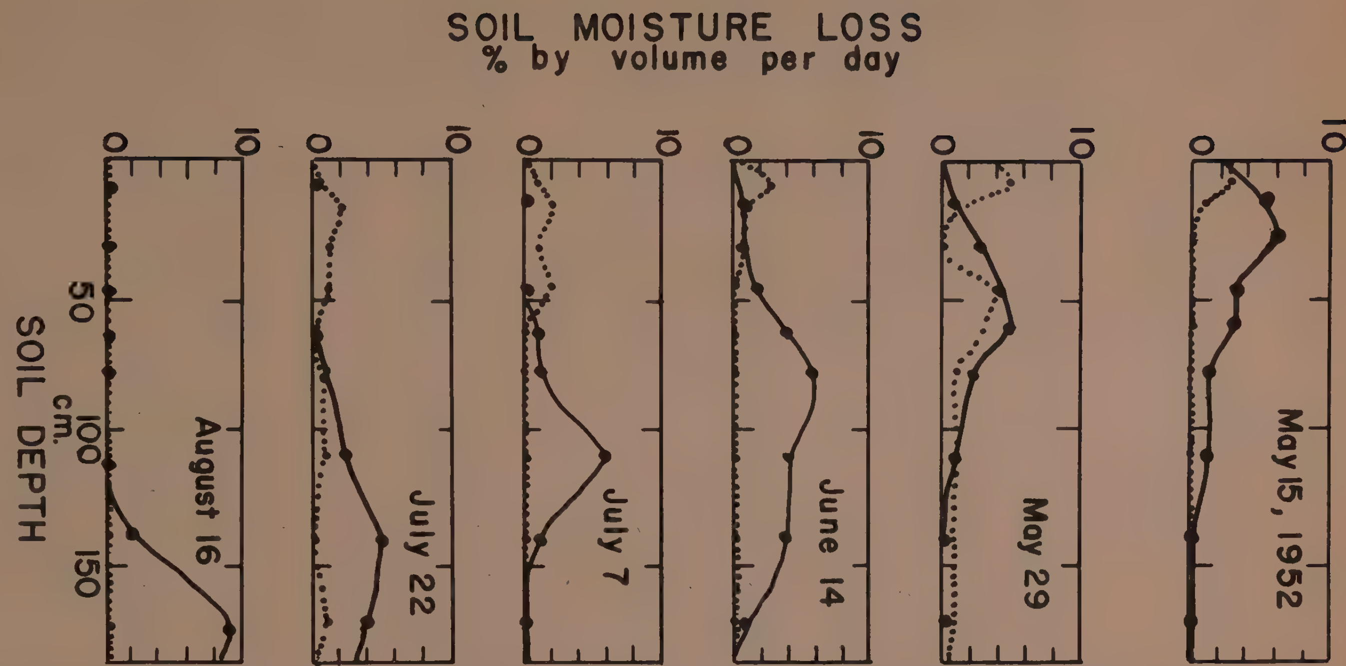

Fig. 9 The rate of soil moisture loss at various soil depths for selected dates during a drying season. Solid line — *Pinus coulteri;* dotted line — Barren.

meter climatic station evaporation pan data were analyzed in relation to the loss from the lysimeter for ten day periods of the soil drying period. The rate of soil moisture loss for a given drying season was correlated with the evaporation pan loss for only a portion of the season. Thus the data for 1955 show the following periodic losses from the evaporation pan and the pine lysimeter in inches:

	March 11—20	March 21—30	April 1—10	April 11—20	May 11—20	May 21—30	June 1—10	June 11—20	June 21—30
Evap. pan loss	1.0	1.8	1.8	1.9	2.4	1.2	2.2	2.0	1.9
Pine soil loss	1.0	1.0	1.0	1.2	1.4	1.4	0.9	0.9	0.4

Thus during this drying season apparently soil and vegetation conditions were independent of the factors that influenced the water loss from the evaporation pan, during the initial portion of the drying season, and the latter portion. During the latter portion the exhaustion of soil moisture is obviously the determining factor, and in the early part of the season the soil moisture loss is constant despite the increasing evaporation pan loss. The latter perhaps being due to the inherent seasonal growth pattern of the trees. The central portion of the drying regime seems less subject to these influences and more subject to the energy factors that affect the evaporation pan loss. The analysis of ten day periodic loss amounts selected from June of each year that had a suitable moisture regime for the evaporation pan and the soil of the pine lysimeter indicated that there was a positive relationship between these losses and the correlated lysimeter soil losses. These ten day periodic water loss amounts when arrayed in order of magnitude of the evaporation pan loss were as follows (inches of water):

Evaporation pan (E)	1.5	1.9	1.9	2.0	2.1	2.3	2.3	2.3	2.6
Pine lysimeter soil ($\triangle$ Qsm)	0.6	0.9	0.9	0.9	1.2	1.2	0.9	1.7	2.0

These data can be described by a linear equation:

$$\triangle Qsm = -1.2 + 1.1 E$$

This relationship would apply only to the month of June for each year in these lysimeters. Further detail is to be obtained from the San Dimas lysimeter data relating climatic variables to soil moisture loss.

HYDROLOGIC RESEARCH USING LYSIMETERS OF UNDISTURBED SOIL BLOCKS

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SUMMARY

The Base Rock lysimeters of the Sierra Ancha Experimental Watersheds in central Arizona afford an unusual opportunity for studying surface and percolation flow in relation to precipitation and vegetational densities in a natural soil mantle.

The installation consists of three lysimeters 5.5 meters wide and 15.2 meters long, having a south-facing slope of 20 per cent at 1219 meters elevation. Undisturbed soil blocks 0.9 to 1.8 meters deep are surrounded by cement walls which are tied into impervious quartzite bedrock.

Surface runoff is trapped at the downslope enclosing wall, which was poured flush with the soil surface to allow free passage of water into the catchment troughs. Percolation flow is picked up through a perforated steel plate at the downslope end of each lysimeter at the soil-bedrock contact. Rates of surface runoff, percolation flow and precipitation are recorded on a multiple-pen strip recorder activated by a 6-volt battery operating through mercury switches.

Separation of surface runoff and percolation flow is important in Arizona because of the nature of precipitation. Summer precipitation is characterized by high intensity thunderstorms that often cause surface runoff. Winter storms are of longer duration but much lower intensities, and water yield usually occurs as percolation flow.

Data from the lysimeters have shown that: (1) Subsurface runoff is an important portion of total water yields; (2) most of the total water yield results from percolation flow during the winter; (3) most surface runoff and erosion are associated with high intensity thunderstorms during the summer; (4) surface runoff and erosion increase as grass densities decrease; and (5) winter water yields appear to be independent of vegetational densities.

RÉSUMÉ

Les Lysimètres de Base Rock des bassins versants expérimentaux de la Sierra Anche dans l'Arizona Central offrent une occasion exceptionnelle pour l'étude de l'écoulement de surface et d'infiltration en relation avec les précipitations et les densités de couverture végétale dans un sol naturel.

L'installation consiste en trois lysimètres de 5,5 m de largeur et de 15,2 mètres de longueur, ayant une pente face au sud de 20 %, à une altitude de 1219 m. Des blocs de sol non perturbé de 0,9 à 1,8 m d'épaisseur sont entourés de parois en ciment qui sont liées au sol rocheux constitué par du quartzite imperméable. L'écoulement superficiel est capté à la paroi du bas de la pente par des auges.

Le débit qui s'infiltre est capté au travers d'une plaque en métal perforé à l'extrémité aval de chaque lysimètre au contact du sol rocheux. Les taux de l'écoulement de surface, de la percolation et de précipitation sont inscrits par un appareil enregistreur à plumes multiples, mû par une batterie à 6 volts fonctionnant avec des interrupteurs à mercure.

La distinction entre l'écoulement superficiel et l'écoulement souterrain est important en Arizona à cause de la nature des précipitations.

Les précipitations d'été sont caractérisées par des orages intenses qui provoquent bien souvent un écoulement de surface. Les tempêtes d'hiver

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sont de plus longue durée mais leur intensité est beaucoup plus faible et leur eau s'infiltre en général dans le sol.

Les résultats des lysimètres ont montré que:

(1) l'écoulement superficiel est une part importante de l'écoulement total; (2) la plus grande partie de l'écoulement total provient de l'infiltration pendant l'hiver; (3) la plus grande partie de l'écoulement superficiel et de l'érosion sont associées avec les orages de forte intensité pendant l'été; (4) l'écoulement superficiel et l'érosion augmentent quand la densité de l'herbe décroît; et (5) l'écoulement d'hiver semble être indépendant de la densité de la végétation.

Undisturbed soil lysimeters afford an unusual opportunity for studying the interrelations of surface flow, percolation, and precipitation in a natural soil mantle. A lysimeter installation is particularly adaptable to studying the disposition of natural precipitation after it reaches the soil, and important information on this phase of the hydrologic cycle can be obtained. The Base Rock lysimeters located on the Sierra Ancha Experimental Watersheds are of the undisturbed block type. The construction of the Base Rock lysimeters is discussed in this paper, together with methods of measurement and some results obtained.

Location of Lysimeters

The Sierra Ancha Experimental Watersheds are on the Salt River Watershed in central Arizona about 64.4 km. north of Globe. The lysimeters are located on an east-facing bench of the watersheds, at an elevation of 1219 meters. The channel at the foot of the slope has eroded to bedrock. A few channels parallel to the slope have also been cut to bedrock. Prior to construction, seepage water during the winter was observed entering the side and main channels at the soil-bedrock contact. This suggested that local precipitation was adequate to satisfy the soil moisture deficit and that studies of surface and subsurface yields would be possible. Location of lysimeters in this area was a natural outgrowth of these early observations.

Objectives of Lysimeter Studies

One objective of the Base Rock lysimeter study was to determine the amounts of surface runoff and percolation flow for the summer and winter periods. Separation of total flow into its components is important in Arizona because of the nature of the precipitation. Summer precipitation is characterized by thunderstorms of high intensity. Under conditions of poor infiltration, surface runoff can be high, and can be accompanied by considerable erosion. Winter storms are of longer duration but lower intensities. Surface and subsurface contributions to water yield can thus be expected to be quite different in summer and winter. A second objective was to study the effect of changes in plant cover upon runoff and erosion.

Description and Construction

Exploration of soil depths overlying the bedrock in the proposed site for the lysimeters indicated a fairly uniform area about 18 meters wide by 15 meters long having soil depths ranging from 0.9 to 1.8 meters. Three

lysimeters were laid out in this particular area. Trenches were first excavated to the bedrock around the entire soil block. Two trenches, 0.86 meter wide, were dug to subdivide the main block. This excavation resulted in the isolation of three blocks of soil each 5.5 meters wide by 15.2 meters long. Soil walls were maintained vertical to minimize soil disturbance.

Rock at the bottom of the trench appeared dense and uniform. It provided a sloping watertight bed ideal for the bottom of the lysimeters. This bedrock is the Dripping Springs Quartzite formation which is a fine-grained, reddish-brown arkosic quartzite and sandstone.

Soils were mapped and evaluated during trenching. The profile contains much disintegrated quartzite rock, surrounded by fine silts and clays that are noncalcareous and acid. Moisture equivalents and wilting coefficients of the soil are high.

Shattered cracked large blocks of rock are present above bedrock in the upslope parts of the lysimeters. Smaller rock fragments are mixed with the subsoil downslope. Depth of topsoil is uniform.

The general arrangement of the lysimeter is shown in Figure 1. Reinforced concrete walls about 15 cm. thick enclose each lysimeter. Concrete forms were used only for the outside walls. Concrete poured against the excavated soil resulted in an irregularly shaped inside wall that reduced water flow along the soil-concrete contact. If an inside form had been used and soil packed between the excavated soil wall and the smooth concrete wall, water flow between soil and concrete might have been favored.

Wall sections were poured to a depth of about 15 cm. in excavated bedrock to insure a good bond between the enclosing walls and the bedrock. Smooth 15 cm. walls were extended above the soil surface on sides and the upslope end to prevent surface water from entering or leaving the individual lysimeters.

The wall at the downslope end of the lysimeters was poured flush with the existing soil surface to permit free passage of surface runoff from the plot into the catchment trough (Fig. 1). Water trapped in this catchment is diverted into tipping buckets for measurement. Percolation flow of water through the soil leaves the lysimeters at the bottom center of the lower end of the soil-rock contact through a 5.1 cm. pipe. The drain pipe at the soil contact is protected by a perforated steel plate to prevent soil from clogging the pipe. Percolation flow is also measured in tipping buckets. No provisions were made for measuring percolate derived at varying depths in the profile. The nature of the material suggested that water would follow the numerous rock-soil contacts to bedrock rather than flow through different soil horizons.

Instrumentation

A multiple-pen, strip recorder measures rates of surface runoff, percolation flow, and precipitation. Charts are mounted on a spring powered drive. Recording pens are actuated by a 6-volt storage battery. A recorder pen makes a mark perpendicular to the direction of the chart travel on each swing of the tipping buckets. The recorder pens are connected to the tipping buckets through mercury switches. One switch is closed on each swing of the 7.079-liter buckets that measure surface runoff; a second switch is closed by splash pans that are attached to a tipping bucket arrangement for measuring percolation flow (47 tips per 10 liters); a third switch is closed by a tipping bucket in the automatic rain gage (.51 mm. per tip). The tipping

bucket rain gage is supplemented by a weighing type recording rain gage for a more accurate measure of snowfall intensity. Runoff leaving the tipping buckets is held in tanks for a volumetric measurement as a check against the tipping bucket record.

Limitations

Lysimeters have inherent limitations. First, they sample small areas of soil and vegetation. Therefore, results must be applied with caution to large areas or to watersheds. Secondly, results from a single battery of lysimeters can be replicated only in time. Thus, a number of years are required to complete any one study or treatment.

The Base Rock lysimeters are limited to one depth of soil. Soil depth is an important consideration in water yields. The 0.9 to 1.8 meters depth of soil on the Base Rock lysimeters limits the application of the findings. Results from deeper soils would permit an extension of the results.

In order to maintain undisturbed conditions there has been no soil excavation or sampling to measure soil moisture or type and depth of rooting.

Size and shape of the plots is another limitation, particularly with regard to the influence it has on the ratios of surface and subsurface runoff. For example, longer plots might decrease the amount of surface runoff and increase percolation flow.

The lysimeters are too small for many types of treatments. For example, grazing treatments comparable to natural grazing use could not be made on the lysimeters. Even when grazing is done by sheep, use is limited to a few days. Grazing with cattle is impractical.

Other factors that cannot be evaluated are: the effect on water yield of seepage along the concrete sides of the lysimeters, development of cracks or channels through the soil, possible differences in bedrock conditions under the lysimeters, and possible existence of perched water tables in the lysimeters.

Erosion measurements are somewhat biased because the concrete wall at the lower end of the lysimeters serves as a base level of cutting. This prevents formation of gullies in the lower part of the lysimeter.

Use of the Lysimeters

Measures of Precipitation-Runoff Relations

Hydrologic information that has been obtained from the Base Rock lysimeters includes intensity and amount of precipitation and amount and rate of both surface runoff and percolation flow. Also, sediment has been measured at the end of the winter season (June 1st) and at the end of the summer season (October 1st).

Precipitation at Base Rock has averaged 448.8 mm. annually. Winter moisture (October through May) from the generally distributed, long-duration, low-intensity storms has contributed 67 per cent of the total. Summer precipitation, mostly from high intensity thunderstorms, but occasionally from a summer storm of large total quantity and intermediate intensities, has made up the additional 33 per cent. An average of about one day in eight in winter and one day in seven in summer have been stormy, but only about 12 per cent of winter storms and 7 per cent of summer storms

have been larger than 25.4 mm. in 24 hours. Very seldom is runoff continuous between storms.

Most of the total water yield comes during the winter as percolation flow from the long-duration, low-intensity storms characteristic of the winter season at the Sierra Ancha Experimental Watersheds. This conclusion is based on figures for average precipitation and water yields by seasons shown in Table 1. Approximately 78 per cent the total water yield can be attributed to winter storms, while runoff in summer has averaged about 22 per cent of the total water yield. Of the 221 summer storms during the first 13 years of record, only 44 produced runoff. The six most intense summer storms accounted for more than two-thirds of the summer water yield for each lysimeter. No runoff occurred during two summers (1939 and 1944). Regardless of surface runoff during the summer, winter precipitation fills the soil mass and winter water yield is largely by percolation flow.

Most erosion is associated with surface runoff caused by high intensity, summer thunderstorms. During the 1935—41 calibration period, soil losses were essentially the same from all lysimeters.

Percolation flow moves rapidly through the soil mass and is practically coincident with surface runoff. This produces high rates of total runoff. For example, during the storm of March 11—15 in 1941, 117.1 mm. of precipitation fell during a 99-hour period. Percolation flow started at 4h 00m March 13, and continued throughout the storm. Surface runoff started at 22h 00m March 13, as a result of a short period of high rainfall intensities (2 minute intensities of 106.7 mm. per hour and 61.0 mm. per hour). The combined surface and percolation flow gave a rate of total runoff of 5.1 mm. per hour over a 3 hour period.

TABLE 1 — *Average precipitation* (1) *and water yield on the Base Rock lysimeters during the calibration and treatment periods*

Treatment of lysimeter	Item measured	Calibration period (1935—41)			Treatment period (1942—53)		
		Winter	Summer	Total	Winter	Summer	Total
		mm			mm		
	Precipitation	345.4	126.5	471.9	269.8	164.5	434.3
Ungrazed	Surface runoff	3.1	1.5	4.6	0.5	7.4	7.9
	Percolation	47.2	0.0	47.2	19.0	7.9	26.9
	Total	50.3	1.5	51.8	19.5	15.3	34.8
Moderately grazed	Surface runoff	5.6	1.5	7.1	0.8	13.2	14.0
	Percolation	45.7	0.0	45.7	22.1	6.6	28.7
	Total	51.3	1.5	52.8	22.9	19.8	42.7
Heavily grazed	Surface runoff	3.0	1.3	4.3	2.1	15.2	17.3
	Percolation	50.8	0.0	50.8	21.8	7.4	29.2
	Total	53.8	1.3	55.1	23.9	22.6	46.5

(1) Winter values are for the months October through May. Summer values are for the months June through September.

TABLE 2 — *Basal area of grass on the Base Rock lysimeters before and during grazing*

Year of Measurement (1)	Ungrazed lysimeter	Moderately grazed lysimeter	Heavily grazed lysimeter
		per cent	
1934	1.29	1.19	1.28
1942	8.56	8.86	6.78
1946	9.16	5.68	2.13
1949	2.74	1.24	0.41
1953	6.11	4.36	3.39

(1) The 1934 measurements were taken before any of the lysimeters were grazed; the 1942—53 measurements were taken during the period when two of the lysimeters were being grazed.

Effect of varying grass densities by grazing

Grazing is the major land use in the vicinity of the Base Rock lysimeters. Improper grazing lowers grass density. One objective for the study was to determine the effect of different densities of grass vegetation, resulting from grazing, on water and sediment yields. During the calibration period between 1935 and 1941, water yields, grass density, and soil loss were about the same for all plots. Starting in 1942 one lysimeter was grazed heavily, and one moderately by sheep. Table 2 shows grass density in terms of per cent basal area. Basal area refers to the percentage of the ground surface penetrated by the grass stems.

Grass densities varied considerably with climatic conditions but were definitely associated with intensity of grazing use. Covariance analysis applied to the data for the calibration period and treatment period showed no statistical significance among winter water yields even though vegetational densities varied considerably. Thus, the water yield in winter appears to be independent of vegetational densities associated with climate and grazing for the soils of these particular lysimeters.

On the other hand, surface runoff was increased during the summer seasons as a result of grazing. As shown in Table 1, the most surface runoff occurred on the heavily grazed lysimeter and the least surface runoff on the ungrazed lysimeter. In spite of increased summer surface runoff, percolation flow from winter precipitation was not significantly decreased.

Erosion losses increased considerably as a result of grazing. Before grazing was started soil loss averaged 21.02 metric tons per square kilometer during the summer. In the winter, it varied from 3.15 to 5.25 metric tons per square kilometer. Following grazing, soil losses from the moderately grazed lysimeter were almost double the losses from the ungrazed lysimeter. Soil loss from the heavily grazed lysimeter was increased more than sevenfold over the loss from the ungrazed lysimeter.

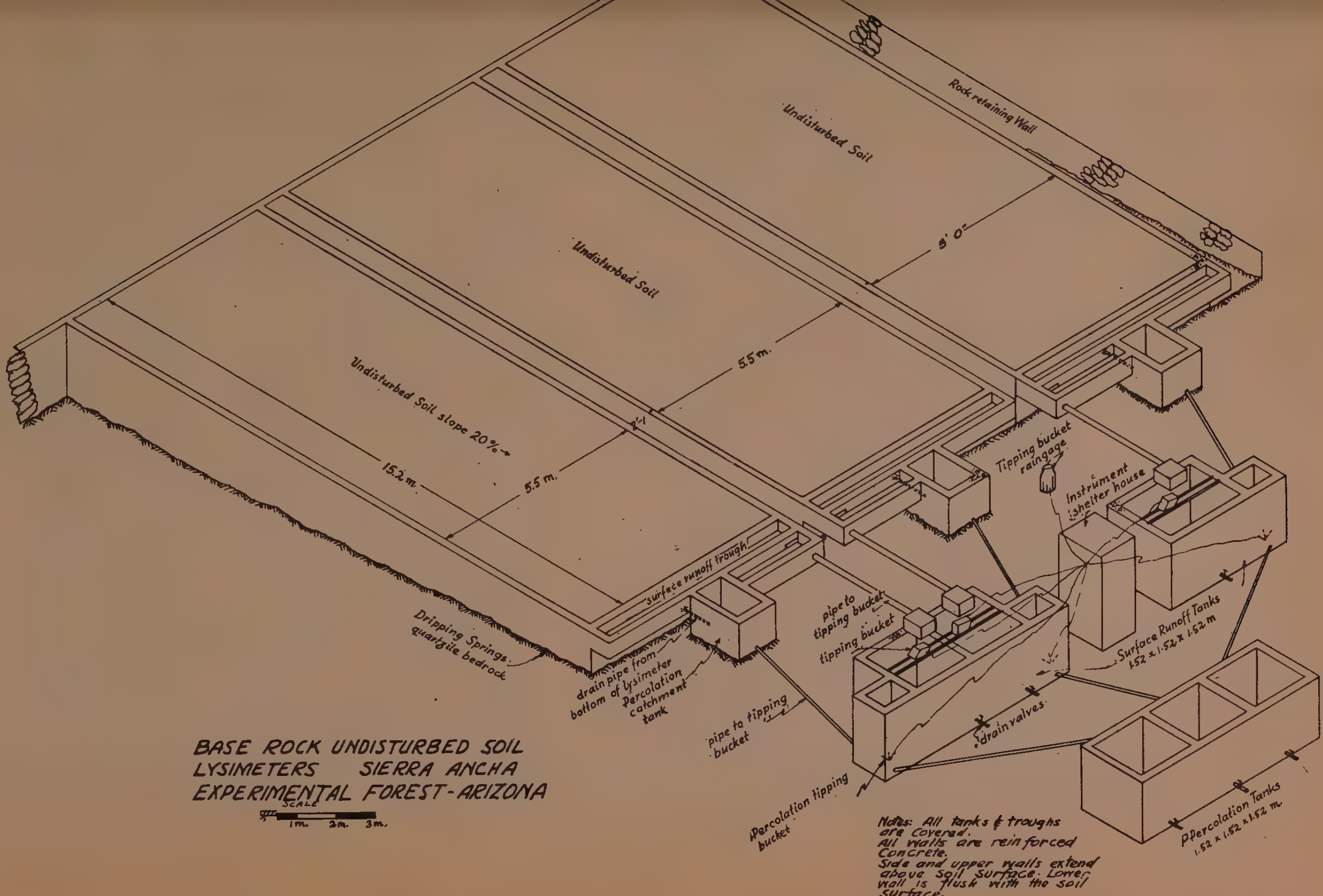

Fig. 1 — Diagrammatic drawing of the Base Rock lysimeters, showing collecting troughs, and instrumentation for measuring surface flow, percolation, and precipitation.

THE EXTENSION OF THE LYSIMETER TECHNIQUE INTO A FIELD METHOD FOR THE DETERMINATION OF THE WATER-BALANCE

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SUMMARY

Lysimeter studies have been concentrated to a greater extent on the study of the water-balance of the soil block in the lysimeter, than on the possibility to make conclusions, from the collected data of the area for which the lysimeter is representative, on the water-balance of that area.

Lysimeter studies are generally done in a way, which does not facilitate the application of these results on the conditions existing in the field. The conditions in the lysimeter are too artificial and vary too little to be comparable with various field conditions.

In the field, data on water content and water movement can only be obtained with reasonable exertion by determination of flow potentials. Groundwater depth, tension in the capillary zone, tensions in the plant and vapour pressures in the air, together make it possible to gain an insight into the movement of moisture and the storage of water, which may account for variations in the amount of water flowing along the path of the transient moisture stream.

If measurements of these parameters of the flow are also executed in the lysimeter tank it becomes possible to relate the data of the lysimeter with those collected in the field. In this way the field observations may be checked and fortified by the accuracy of the lysimeter, while at the same time maintaining the adaptation to the varying conditions possible in the field.

The limitations of the possibility to transfer the lysimeter results to the field, represent the shortcomings of this apparatus, that need most urgently to be remedied.

RÉSUMÉ

Les études lysimétriques se sont concentrées davantage sur l'étude du bilan d'eau dans le bloc de sol se trouvant dans le lysimètre que sur la possibilité de tirer, des données recueillies dans une région de laquelle le lysimètre est représentatif, des conclusions s'appliquant au bilan d'eau de cette région.

Les études lysimétriques sont généralement exécutées de telle manière qu'il n'est pas aisé d'appliquer leurs résultats aux conditions existant en plein champ. Les conditions dans le lysimètre sont trop artificielles et trop peu variées pour être comparables aux diverses conditions en plein champ.

En plein champ, les données sur le contenu d'eau et sur le mouvement des eaux ne peuvent être obtenues sans trop de peine que par détermination des potentiels d'écoulement. La profondeur de la nappe phréatique, la tension dans la zone capillaire, les tensions dans les végétaux et les tensions de vapeur dans l'air, ces données réunies permettent de se former une idée du mouvement de l'humidité et de la rétention d'eau, qui peut être responsable de variations de la quantité d'eau se déplaçant le long des lignes de courant.

Si les mesures de ces paramètres du courant sont également réalisées dans le réservoir du lysimètre, on sera à même d'établir la relation entre les données lysimétriques et celles que l'on recueille en plein champ. De la sorte, les observations faites en plein champ pourront être vérifiées et confirmées par l'exactitude du lysimètre, sans négliger pour cela l'adaptation aux différentes conditions qui peuvent exister en plein champ.

La posssibilité limitée de transposer les données lysimétriques aux conditions en plein champ constitue un défaut de cet appareil, défaut auquel il est très urgent de remédier.

The progress due to the lysimeter

Up to now the lysimeter has proved to be the most refined and the most reliable instrument to study the water-balance. The lysimeter that can be weighed, gives the most accurate results. This type of lysimeter has given a deep insight into evaporation, sub-soil run-off and storage variations. The greater part of the working knowledge with respect to the total need of water for irrigation, or to the amount of water to be drained away, has come from the confirmation the lysimeter could give to the empirical evidence. It should be admitted that the aims of the lysimeter studies, taken as studies on the water-balance of the soil block in the lysimeter, have been nearly fully attained. This has given normative figures for use in land development programs, sprinkling irrigation, etc.

The study of the lysimeter has given the most valuable results where general problems were concerned. Where the lysimeter was planned to give more or less accurate data about run-off, storage or evaporation of a well-defined area the research worker is confronted with a problem of a different nature than that concerning the study of lysimeter data as such. In the first mentioned case the problem has to be solved, what the observations on the separated soil block point out with respect to the water-balance of the area under consideration. The number of studies aiming at the prognosis of the water-balance of an area based on observations of a lysimeter, is less than those of the lysimeter proper. Here a new problem is met, namely how to make determinations which enable one to compare situations in the field with those in the lysimeter and how one should decide, what determinations should be made.

While the possibilities to make a valuable study of lysimeter data proper seem to decrease gradually, there is still ample scope for valuable progress in the comparison of soil block- and field data.

The limitations of the lysimeter technique

As already mentioned the type of lysimeter that can be weighed is the most accurate. Weighing is no longer possible, however, if the volume of the block of soil to be studied is too large, or when by means of some hydrological artifice one has been able to separate a uniform piece of land from a larger area. The determination of the moisture content by sampling or by some electrical device may then give the required data concerning the moisture volume of the profile under observation. The lysimeter technique itself is based on the measurement of volumes or weights.

It is not very easy to describe the water management of the block of soil in the lysimeter with data on rainfall, run-off and moisture storage. Errors of observation and the often rather long-time intervals between successive readings of the variables involved, increase these difficulties. But if such a description of the water-balance might succeed with a satisfactory accuracy, even than it would not be a simple matter to establish the validity of these results for the area for which the lysimeter is representative. The situation in an area of some size cannot be regarded without further conditions being identical with the always somewhat artificial circumstances in the lysimeter. The weak point in the lysimeter technique is the difficulty to transpose the results from the tank into the field. This is proved by the fact, that in the study of the water-balance of an area the information from a representative lysimeter very seldom plays a prominent part.

The lysimeter in normal use yields informations of a limited nature. The measurements are concentrated on the determination of the run-off. This means, that the optimal applicability of the lysimeter will be found there where the sub-surface run-off can also be determined in the field. Should no parallelity exist between the run-off determined in the field and that determined by means of the lysimeter, then the limitations of the significance of the data on evaporation and storage of the lysimeter for the water-balance in the field would already be pointed out.

Where—as in flat polder areas—the run-off can easily be measured, the lysimeter may be valuable. Where—in sloping areas with groundwater streams that cannot be predicted—the sub-surface run-off is not measurable, the results of the lysimeter are difficult to transfer into the field. The lysimeter is here only a check of restricted reliability for measurements in the field.

A measuring technique for the field

The measurements necessary for the determination of the water-balance in an area of some size are not, as in the case for a small plot, to be executed as determinations of volumes or weights. For such larger objects various techniques are customary in other fields of research. These techniques distinguish between the determination of properties of the object under consideration, that are permanent, and conditions that vary. These variable conditions are measured as tensions, pressure-heads or pressure-gradients. The permanent properties are cross-sectional areas of flow and permeabilities or streamflow resistances, which are determined once and for all by measuring only once or with a restricted number of repeats.

In the complete water-balance formula the different magnitudes for run-off, evaporation and so on, are linked together with the equation of continuity which applies to every flow of water.

We suppose a cubiform space is situated in the path of the stream-flow. Now the equation of continuity points out, that the difference in the quantities of water flowing in and out of the cube is equal to the amount of water, which is stored in or removed from the amount of moisture in the cube. The storage in the different parts along the trajectory is governed by distinct relations. Storage depends on the properties of soil and crop, but also on the magnitude of the moisture-stream. It will be necessary to make use of the potentials and of the storage properties of every section of the flow-path if one tries to explain a single balance-term as evaporation, interception, run-off or storage in the ground.

The combination of measurement of quantities with measurement of flow velocities

When comparing measurements of the lysimeter with measurements in the field it will be very useful to work with the same method. Now the determination of moisture volumes or weights is not easily done in the field. The determination of moisture-flow with the aid of measurements of potentials is however indeed possible in the lysimeter-tank. This method of measuring potentials may serve as a link between the lysimeter study and the field-work.

The technique of measuring volumes or weights gives results with a high accuracy and this makes the lysimeter a valuable apparatus for checking

results of the stream-flow determination. The latter technique is less accurate, but is simpler to expand over larger areas. This makes a close adaptation possible to local changes in hydrology and the setting up of sub-balances that may show the influence of varying conditions.

The best way to include the results of a lysimeter in the study of the water-balance of an area is to make use of the double testing-function which this apparatus may execute. The weights and volumes measured in the lysimeter must agree with those calculated from the potentials, determined in the same soil block. This is a comparison of the two methods. The relation between potentials and flow intensities in the lysimeter must agree with the relation existing between the same variables in the field. This checks to what extent the soil block in the lysimeter is representative of the situation in the field, that is, checking the constants in the formula.

Checking the field-work is important. It is necessary to test the flow function itself as well as the constants in the function. It is also necessary to know the separate terms of the water-balance with respect to their absolute value under constant circumstances, and as much, the influence of a variation of circumstances on the change in the terms of the water-balance.

Repeatedly one has tried to increase the significance of the lysimeter by the execution of supporting determinations. Often these were typical lysimeter methods, for instance the Popoff-lysimeter. These determinations frequently are not easily executed in the field or do not reveal much about the object in its undisturbed condition. Here the improvement is sought in the lysimeter itself and not in the possibility of transfering results. With this kind of auxiliary determinations not much advance in knowledge can be expected.

Which tensions can be measured?

Each term of the water-balance is mainly governed by a definite property of the soil. If one is interested in a certain term of the balance, it will be necessary to determine the property that determines this part of the water-balance. This is not only the case for soil constants. The potentials, that can best be determined, also depend on the term of the water-balance that attracts the most attention in the research-work. For run-off studies these are the permeability and the pressure-gradient in the groundwater. If evaporation studies are made, one will sooner think of measuring the moisture tension in the soil and the evaporation capacity of the atmosphere. Each section of the stream-flow path has its own obvious measurements, that determine tension and stream-flow in this section best. For several points along this path it will still require a considerable amount of research to obtain a method, that may be easily executed in the field, that gives a good insight in the stream-flow and that does not disturb the crop and the soil profile too much.

In the next paragraphs we will describe the stream-flow in the saturated zone, the capillary zone, the flow through the plant, the movement of vapour through the atmosphere and the measurements to be made to determine the quantities of flow.

The flow of the groundwater

The flow of the groundwater is governed by the pressure-gradient, the size of the aquifer and the permeability.

In the lysimeter this problem is omitted, the discharge is collected in its entirity. Supplementation in dry periods takes place in well-known quantities. Measurement of flow by means of pressure-gradients of the free water is not possible.

For the field it is sufficient if the gradients are known along a few aequipotential lines, which cut through the entire area of flow. Depth of the water-table is measured easily and it may be done with advantage on a number of control points as well. Where the permeability of the sub-soil is erratic and the thickness of the aquifer variable, the determination of the sub-soil run-off may prove to be difficult. Surface run-off will have to be measured separately.

The capillary flow

The flow through the capillary zone is governed by the capillary tension and the capillary permeability. The difference in tension might be determined by measuring the groundwater depth and the tension somewhere in the capillary zone. Tensiometers and gypsum- or other blocks may serve as expedients for this determination. In some cases one may succeed in deducing the tension from the moisture content and the pF-curve, or from the storage capacity, the groundwater depth and the pF-curve. Where the tension can be deduced from other data, the measurements of the pF in the same zone have clearly the function of a means to increase the accuracy and of checking the other data.

The flow of moisture in the plant

It would be important if indications concerning the moisture tension could be obtained from the plant itself. The description of the physics of the flow through stem and leaves is still the least well-known section of the chain of flow. In literature, methods to determine the quantity of flow in stems and leaves are mentioned. The determination of the width of opening of the stomata is also possible. There is still insufficient certainty concerning the usefulness of these methods for the determination of direction and intensity of flow. The upward flow can up to now be determined easier in the capillary zone of the soil. A reliable determination in the section of the path consisting of the plant tissues would strengthen our knowledge about the flow in the capillary zone as well as in the atmosphere. The determination of the opening of the stomata—the width of which is controlled by the moisture tension in the plant and the radiation—seems to offer the widest perspectives. The importance of the determination of the quantity of vapour moving through the leaves will be clear when considering the regulating function of the plant in the process of evaporation. The difficulties, that have to be overcome will be clear as well. The irregularities in evaporation with respect to time as well as to the place of the leaf in the canopy can be considered as a main problem. If one realises, however, that it is already sufficient to establish a potential at one single point of the flow path, only a limited part of the problems on the influence the plant exerts on the evaporation, need to be solved. This tension need not even be expressed in cm. or atmospheres, relative data may already do. The absolute value of the quantity of flow can be better measured in that section of the path where the absolute values can be determined in a more simple manner.

The vapour transport in the air

The measurement of the displacement of moisture in the air can be divided into the measurement of the rainfall and the measurement of the evaporation. Rainfall on short crops is easily determined. It is, however, a shortcoming that so seldom the amount of moisture is determined that is intercepted by the canopy. In forests, interception is now and then added to the rainfall measurement as an additional determination. But for less high vegetation such a determination seems to be advantageous also.

Many attempts are made to determine the evaporation from the vertical vapour transport by measuring the wind velocity and the relative humidity at various heights. Many difficulties still will have to be overcome in this respect. The ultimate solution of the problem of the vertical vapour transport will undoubtedly succeed sooner, if the evaporation of crop and soil surface can be determined with other methods with a higher frequency. The measurement of the moisture-stream, discussed here, with determination of the flow potentials along the path of the flow at different places in the saturated zone, the capillary zone and the plant, may well serve as this test method.

Auxiliary determinations for the lysimeter and main determinations in the field

If one considers what might be done on the potential determinations as suggested, with only limited exertion, the installation of measuring-wells seem to deserve consideration first. The groundwater table and the groundwater stream should be rather regular however. On mountain sides or in places with rocks in the underground, measurement of the water table will only to a lesser extent further the solution of the water-balance. Measurement of the water table depth has the advantage that it is simple and reliable.

The capillary tension can be measured with tensiometers in that part of the profile, that does not dry out too much. These measurements are less reliable than the measuring-wells, but still easily to be done. Gypsum- or nylon-blocks may be used for the determination of the moisture tensions as well as of the moisture content. These measurements are far less easily carried out. The reliability of the measurements of the tension is decidedly larger than the determination of the moisture content. Though these measurements with resistance-blocks require much care, they are certainly in place in the lysimeter, somewhat less so in the field. The tensiometer may be used in the lysimeter and in the field with success. Tensions higher than pF 2.5 are of too limited importance for capillary flow and need not be determined.

Measurements on the crop itself have been done to a small extent only. Here the possibility to apply the measurements as a routine-method does not seem to exist up to now. It does seem of importance, however, to stimulate research in this direction.

The determination of the relative humidity of the air in and above the vegetation has been tried as a method to determine the evaporation and dew-formation in many places in the world. This determination of the vertical vapour-transport is a determination particularly used for larger areas and it would have only a restricted significance if applied in lysimeter research. The determination of relative results with this method will undoubtedly be simpler than the elaboration of it to an absolute measurement.

If measurements of the vertical vapour-transport are included in the sequence of measurements of the moisture-flow through the other sections of the path of flow, the various measurements might support each other mutually. Taken together, the methods might give a reliable result. Alone, several of the methods may not be able to establish any part of the water-balance with any accuracy.

As supplement to the already mentioned techniques a few measurements may further be considered. The new moisture determinations with γ-rays and the measurement of the difference between air- and leaf temperature deserve consideration for example.

The minimum number of conditions to be measured

Many of the measurements mentioned are to be considered as supplementary to the four series of observations that constitute the minimum necessary. These four series consist of the head of pressure at the lower end of the flow-path, the head of pressure at the point in the field to be studied, the rainfall intensity and the evaporating capacity of the atmosphere. The determination of the quantities of water that comprise the water-balance, based on this utter minimum of observed variables, will however lead to a less accurate result for those terms of the balance that are the least directly governed by the four observed properties. Each section of the flow-path will be the most accurately described by the gradient measured in the section itself by measuring at both ends of that section. If such a tension is not measured, but determined indirectly, the end solution will gain by adding a direct measurement to check the indirect determination. The capillary tension in the root-zone will be the most valuable determination in this respect.

The absolute value of the amount of flow can be obtained in the simplest way from the rainfall observations. But the discharge of the watercourse or tile-drain may also give this absolute quantity. The use of both quantitative measurements will give the highest accuracy. This will, however, also involve the researcher in a difficult process of adjustment.

In the lysimeter, with a fixed water table, no head of pressure is present to aid in the calculation of the run-off. The measured amount of drainwater must be considered as one of the main of the four series of measurements. In a lysimeter without a water table, a capillary tension will have to be determined to obtain a head of pressure at the end of the path. Without such a determination, made at the bottom of the lysimeter-cylinder, one would fail to have a zero plane for the pressure-gradient.

MOISTURE MOVEMENT IN UNSATURATED (THREE-PHASE) SOILS, WITH SPECIAL REGARD TO THE UTILIZATION OF LYSIMETER OBSERVATIONS

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SUMMARY

Moisture movements in unsaturated soils are highly insolved even under isothermal conditions. Such conditions, however, never occur in practice for the temperature of the soil varies with time from point to point. This tends to further complicate the phenomenon of moisture movement, since the temperature gradient and change in temperature result in vapour flow in the soil. Vapour movements due to daily fluctuations in soil temperature are of particular significance.

In case of a groundwater table at moderate depth (down to about 3 m.) daily fluctuations therein occur on days, on which the upper soil layers warm up considerably and the temperature variation is great *(Fig. 1)*. A general characteristic of this is the lowering table from morning until the afternoon and a slight rise during the night *(Fig. 3)*. No daily fluctuation in the groundwater table takes place in winter and in autumn, *(Fig. 2)* and on summer days, on which the upper soil layers cool down appreciately *(Fig. 5)*. This phenomenon can be explained by the fact, that in order to maintain the saturation vapour pressure in the soil pores at rising temperature a considerable amount of water changes into the vapour phase and condenses back to water upon cooling *(Fig. 4)*.

Evaporation from the soil as well as the moisture content and the distribution thereof depends upon the vapour movement in the entire depth of the unsaturated cover above the groundwater table. In case of artificially bounded soil prisms both evaporation and—owing to the different distribution of moisture—infiltration may materially depart from those of natural soils. In case of lysimeters artificial lower boundaries must of necessity be applied. Water balance of the upper and lower layers and variations in groundwater are closely related by the movement of vapour. Therefore, funnel lysimeters may yield but relative values for infiltration, and the natural water balance of the soil cannot be approximated even by weighable lysimeters unless these extend down to below the groundwater surface.

AUSZUG

Im ungesättigten Boden ist die Bewegung der Feuchtigkeit auch bei isothermalen Zuständen recht kompliziert. In der Natur gibt es aber keinen isothermalen Zustand, die Bodentemperatur wechselt nach Zeit und Lage. Demzufolge gestaltet sich die Feuchtigkeitsbewegung noch komplizierter, da im Boden auf Einwirkung des Bodentemperaturgradienten und der Temperaturänderungen Wasserdampfströmungen entstehen. Besonders bedeutend ist jene Wasserdampfbewegung, welche die Tagesschwankungen der Bodentemperatur hervorrufen.

Bei geringer Flurtiefe des Grundwassers (bis ca. 3 m) zeigt sich an Tagen mit stärkerer Erwärmung der oberen Bodenschichten und großer Temperaturschwankung eine Tagesschwankung des Grundwasserspiegels (Abb. 1). Diese kennzeichnet im allgemeinen eine Senkung des Spiegels von früh bis nachmittags und ein Aufsteigen abends und in der Nacht (Abb. 3). Im Herbst und Winter (Abb. 2) sowie an Sommertagen, an welchen sich die oberen Bodenschichten stark abkühlen (Abb. 5), zeigt sich keine Tagesschwankung. Diese Erscheinung kann damit erklärt werden, daß bei Erwärmung zur Aufrechterhaltung des Sättigungs-Wasserdampfgehaltes der Bodenporen eine größere Menge flüssigen Wassers in die Dampfphase übergeht, welche sich bei Abkühlung wieder kondensiert (Abb. 4).

Die Bodenverdunstung, sowie der Feuchtigkeitsgehalt und dessen Verteilung sind von der Dampfströmung abhängig, welche in der vollen Dicke der über dem Grundwasserspiegel liegenden ungesättigten Bodenschicht stattfindet. Bei künstlich abgetrennten oberen Bodenkörpern kann die Verdunstung und — infolge der verschiedenen Feuchtigkeitsverteilung — auch die Einsickerung ganz anders vor sich gehen, als bei Naturböden. Bei den Lysimetern muß immer eine künstliche untere Abgrenzung angebracht werden. Das Grundwasser, sowie der Wasserhaushalt der oberen und unteren Bodenschichten sind besonders infolge der Wasserdampfströmungen in engem Zusammenhang. In Anbetracht dessen werden mit Trichterlysimetern auch für die Versickerung nur relative Werte erhalten und die Waagenlysimeter nähern den natürlichen Wasserhaushalt des Bodens auch nur in dem Fall an, wenn sie bis unter den Grundwasserspiegel reichen.

Data directly suitable to practical evaluation on three factors of the water balance which cannot be determined readily, namely on *evaporation, infiltration* and *storage* both in the soil and groundwater, cannot be obtained by lysimeters, unless natural conditions can be approximated fairly by these. General specifications relating to the conservation of the original soil structure, the minimum practicable dimensions, the arrangement of the station in harmony with its surroundings, etc. have been developed for the arrangement of lysimeters on basis of experience [1, 4, 5, 6]. However carefully these rules are adhered to, an artificial boundary at smaller or greater depth is yet unavoidable in case of lysimeters. The question arises whether the water balance charcteristics of the soil of which the upper 1 to 3 m. deep layer is artificially separated from the lower ones, remain the same as in the case where it may freely communicate with the underlying strata.

In order to arrive at conclusions concerning the correct operation of various lysimeter types, the movement of water in the soil containing air and water alike (three-phase soil), and the changes therein caused by lysimeters should be investigated.

In dealing with the infiltration of precipitation water into the soil, previous theories tended to neglect all forces besides gravity, and endeavoured to approximate all water movements in the soil by the Darcy law or by empirical formulae derived therefrom and containing minor modifications. It is well established by to-day, that water movements in unsaturated soils are governed by the simultaneous action of several forces [2, 9, 10, 11, 12, 16].

Water within the soil may move in two phases, namely, as vapour or as liquid. Under isothermal conditions movement in the form of vapour is caused by the partial vapour pressure. Water in the liquid phase is under the influence of various forces. These are: gravity, the surface forces of soil particles *i.e.*, the so-called adsorptive forces, the electric field of the hydrosphere surrounding the soil particles (sorptive forces) and the capillary or meniscus forces in the pores of the soil the water-air interfaces [2]. The aggregate effect of forces acting on the soil moisture can be expressed by the total potential of soil moisture, which depends upon the physical properties of the soil, the nature of the voids and the moisture content.

Under isotermal conditions the liquid water movement is predominent and the flow of vapour is of subordinate significance. Liquid flow (Q) is initiated by gravity and the capillary potential including all other forces simultaneously (referred to also as free energy of the soil, or the tension of soil moisture). Water movement in this case can be described by the following expression:

$$Q = - K' \text{ grad } \Phi = - K' \text{ (grad } \psi + \text{grad } \varphi) \ldots (1)$$

where:

K' = the specific hydraulic conductivity depending upon moisture content

grad Φ = the gradient of the total potential

grad ψ = the gradient of capillary potential

grad φ = the gradient of gravity force potential

Depending upon the moisture content of the soil, at smaller values thereof it is the capillary potential, whereas at greater values the gravity force that mainly influences liquid water flow. The critical moisture content (θ_K) characterizing the commencement of gravitational water movement is slightly higher than the highest molecular water capacity established by *Lebedjev* and may be described by a capillary potential value p_F = 3.2 to 3.1. Approximating values of the critical moisture content for various soils are as follows:

Sand	2- 5	per	cent	by	weight
Sandy loam	5-10	„	„	„	„
Loam	10-21	„	„	„	„
Clay loam	21-28	„	„	„	„
Clay	28	„	„	„	„

No detailed discussion of moisture movements due to gravity and capillary potential will be given here and the reader is referred to the literature on the subject [2, 9, 10, 12].

The movement of soil moisture is yet more involved under conditions occuring in nature, owing to the variation in soil temperature with time and location which also gives rise to soil moisture movements. The momentary temperature of the soil, and variations with time and location therein, are governed by various thermal properties of individual soils. Under moderate climates daily fluctuations in soil temperature can be observed down to depths of about 1 m. in summer, whereas in general down to 20 to 30 cm. in winter, Neglecting daily fluctuations, which, is permissible in winter below about 20 cm., and in summer below about 50 cm. depth the soil temperature may be regarded as constant for short periods, and under the influence of the soil temperature gradient corresponding to the variation with depth in temperature, mainly vapour, respectively, water movement occurs in case of low and high moisture contents. In the period from October to February the lower layers are warmer, and, accordingly, upward moisture movement should be anticipated, whereas it is the upper layers that become warmer from April to August, and the direction of moisture movement is reversed in this period. March and September are usually of transitory character, when there is usually no appreciable vertical temperature gradient in the soil. Moisture movement due to a temperature gradient constant with time can be traced fairly accurately by mathematical methods [7, 11, 12, 16]. Considering, that the temperature gradient is higher in the air-filled pores than that related to the entire soil mass [11, 17], the order of magnitude of upward or downward moisture movement due to the soil temperature gradient may be characterized by the limits

$$10^{-7} \text{ to } 10^{-9} \ \text{g cm}^{-2} \text{ sec}^{-1}, \text{ or else}$$
$$10^{-2} \text{ to } 10^{-4} \ \text{g cm}^{-2} \text{ day}^{-1}$$

Allowing for no more than the abovementioned forms of soil moisture movement it is to be seen, that the movement of water in the upper layers is in these cases influenced by the moisture content of the lower layers even if the extent of this influence is less significant. These types of move-

ment are, however, still insufficient for obtaining a reliable picture about evaporation from the soil and from groundwater. Upward movement of moisture due to the soil temperature gradient occurs only in winter and is even then very slight, the order of magnitude of evaporation from the soil computed for isothermal conditions being no more than 10^{-6} gcm^{-2} sec^{-1}, *i.e.*, 0.8 to 1.0 mm/day [12, 16]. Evaporation from the soil and the reduction of the groundwater volume are materially greater in the summer months. The discrepancy can be attributed to daily fluctuations in soil temperature. As revealed by experiments into waterbalance, which have been conducted in Hungary for several years at the experimental station of the Research Institute for Water Researches in Kecskemét, *moisture movement in the soil is to a great extent influenced by daily fluctuations in soil temperature*, and, therefore, *the relationship between groundwater and the waterhousehold in the upper and lower layers is a very close one.*

The experimental station is located in the roling sand country between the Danube and Tisza Rivers [14]. The soil consists of a medium graded dune sand which can be regarded as completely homogeneous for all practical purposes.

The gradation of the sand is the following

0.5 to 0,2 mm.	15 per cent by weight
0.2 „ 0.15 „	25 „ „ „ „
0.15 „ 0.1 „	30 „ „ „ „
0.1 „ 0.07 „	20 „ „ „ „
$<$ 0.07 „	10 „ „ „ „

The effective grain size is 0.13 mm., the total pore volume n = 0.35 to 0.38 and the free pore volume is approximately n_0 = 0.23. The groundwater table is located within the same sand layer which at the same time forms the unsaturated cover above the groundwater. Surface runoff is zero, and neither inflow or outflow of groundwater can be observed. These conditions were very favourable for a detailed study of soil moisture household. Both water storage in the soil and any reduction in the stored volume occur in the experimental area purely as a result of vertical moisture movement through the covering layer. In addition to continuously recording groundwater stages and meteorological data, the moisture content of the soil is measured daily and data are collected by three non-weighable funnel lysimeters [14].

It could be observed among others, that in cases where groundwater table occupies a position close to the surface (down to about 3 m.) *appreciable daily groundwater fluctuations occured in some periods.* The observation of this phenomenon was rendered possible by the groundwater gage having an accuracy of one mm., by the aid of which readings have been taken every second hour during the past five years on the groundwater table. Each year, beginning usually with the end of April and lasting until October, when the upper soil layers are warmer than lower ones and when range of daily temperature variations is wider, the groundwater table carries out daily fluctuations. The extent of this is considerable and on warm days with no precipitation, extreme values of 9 to 10 cm have been observed.

Characteristics of daily groundwater fluctuations observed in spring and in summer are represented for the sake of illustration in *Fig. 1.* Periods of 10 days are shown in the figure. For instance the groundwater table is still slightly high at the beginning of May 1958, yet also daily fluctuations become apparent already. The latter is increased steadily during the spring and sommer months, accompanied by the simultaneous drop of the groundwater

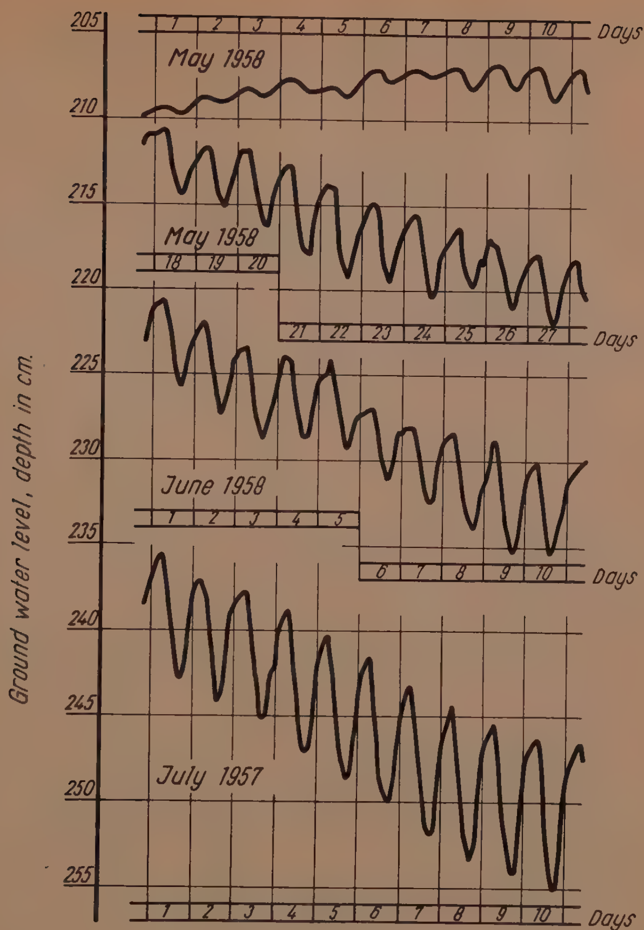

Fig. 1 Characteristic daily fluctuation in the groundwater table occuring on warm days.

table. A general trend that can be observed is, that a drop ensues from morning to the afternoon, while the groundwater rises during the evening and the night. No precipitation fell during this period corroborating the fact, that a rise in groundwater level is possible also without precipitation. Periodical changes in the groundwater table could not be observed in autumn and in the winter (*Fig. 2*).

Similar daily fluctuations can be observed only on days, on which the temperature of the upper soil layers rises appreciably during the daytime hours. On days, in which there occurs a drop in the temperature of the upper soil layers due to a cold spell or precipitation, the daily fluctuation disappears even in summer.

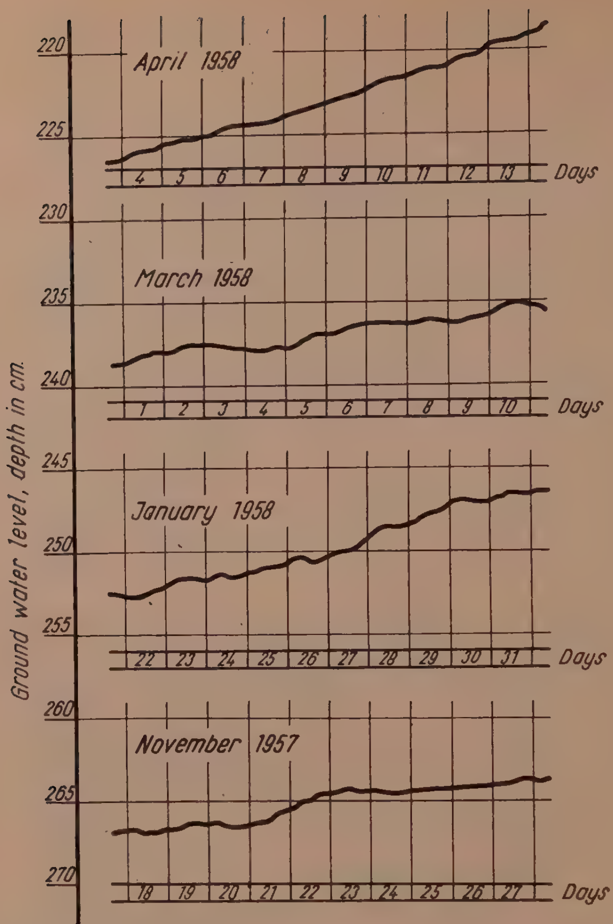

Fig. 2 No periodical daily fluctuation in the groundwater table occurs in the winter and autumn months.

Conditions under which this phenomenon occurs should be investigated in detail subsequently. Observed values are given in *Fig. 3* for three very warm days, which were preceded by a dry period of several days duration (6, 7, 8 July, 1957). Daily groundwater fluctuations between very wide limits were observed during these days. The moisture content of the soil at depths between 20 and 60 cm was 3 to 3.5 per cent by weight, and was thus slightly higher than the maximum hygroscopicity (Hy). The trend of soil temperatures measured at different depths is shown in the upper part of the figure (a.). As to be seen, the upper layers are always warmer than the lower ones, and a very marked temperature increase can be noted especially in the daytime hours. Fluctuations of the groundwater table at depths from

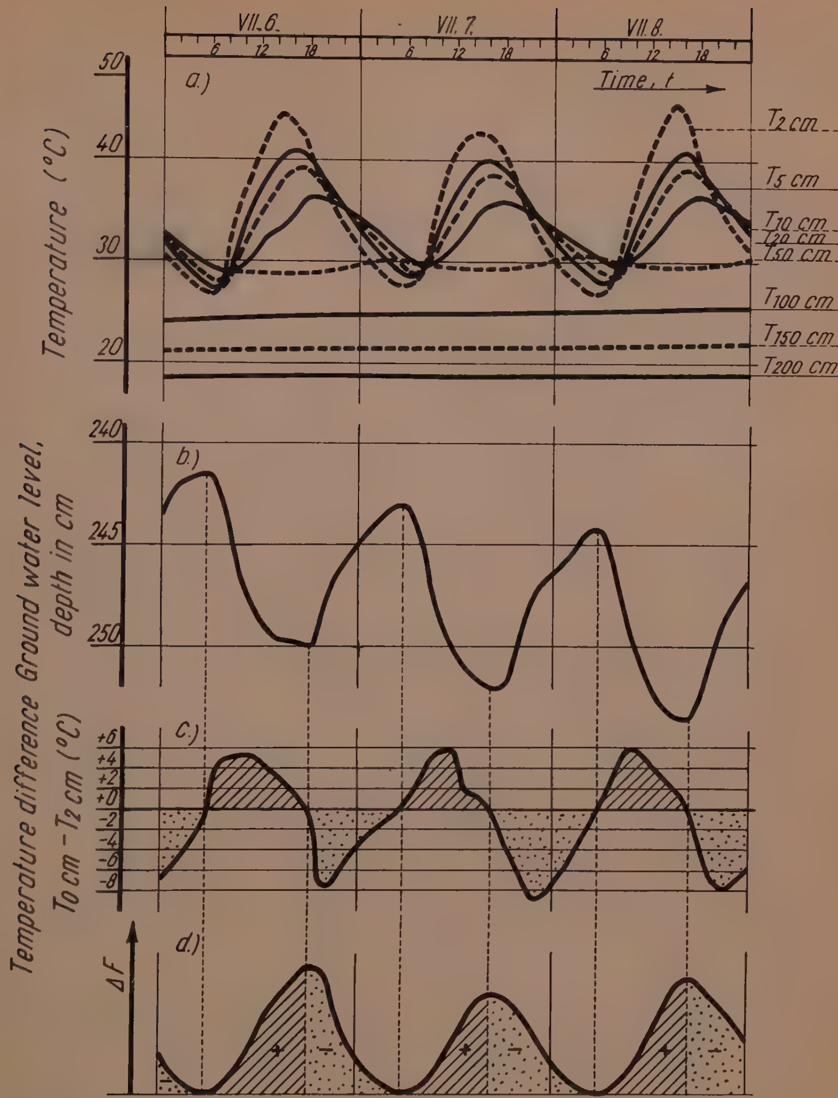

Fig. 3 Detailed study of daily groundwater fluctuations

a.) variation of soil temperature (T) at various depths

b.) groundwater table fluctuations

c.) temperature differential between the surface and 2 cm depth $(T_{0\,cm} - T_{2\,cm})$

d.) variation of the saturation vapour content (Δ F) of the layer between 2 and 50 cm depths.

240 to 255 cm have been entered thereunder (b.). The daily drop in the groundwater table begins at the time, when the temperature of the upper layers starts to increase. From the afternoon until morning the upper soil layers cool down and the groundwater table rises simultaneously. The temperature of deeper layers follows that of the upper ones with a certain time lag only. Fluctuations in the groundwater table were found to be governed by temperature changes in the upper layers. The trend of the differences between the temperature at the soil surface and at 2 cm. depth ($T_{0\,cm}$-$T_{2\,cm}$) is plotted in the third part of the figure (c.). The groundwater table can be seen to drop in periods ,where the temperature of the soil surface is higher, and an instantaneous rise can be observed whenever the soil surface cools to a temperature lower than that prevailing at a depth of 2 cm.

If the moisture content of the soil is higher than the maximum hygroscopicity, then the voids in the soil are filled by vapour. The amount and partial pressure of vapour at saturation depend upon temperature and increases sharply together with the latter, especially at higher temperature values. Vapour saturation of the voids with increasing temperatures cannot be maintained unless a considerable supply of water is available. *The daily fluctuation of the groundwater table can be explained by the great amount of water which changes in the range of temperature fluctuations into the vapour phase to be condensed again upon cooling.* As indicated by observations the movement of vapour caused thereby is of very high velocity and significant enough to result in changes directly in the groundwater volume. The lower part of the figure (d.) shows the trend of changes in the saturation vapour content (Δ F) of the layer between 2 and 50 cm depths.

According to experience gained from these observations, the phenomenon can always be explained by the described process, however, the mathematical treatment thereof, and a quantitative analysis in particular, is at the present state of knowledge not yet possible. A vapour movement opposite to the temperature gradient ensues in the daytime hours under the influence of daily temperature changes in the upper soil layers. The increase in saturation vapour content following the warming up of soil voids is considerable, but is not related to the change in groundwater volume corresponding to the fluctuation the groundwater table. Even in the case of a very high void air-content at very slight moisture content, computed values of the maximum daily variation in saturation vapour content corresponding to the change in soil temperature are about 2 to 2.5 g/m^2.

On the other hand, if the change in water volume corresponding to the fluctuation of the groundwater table is computed for the entire free pore volume, the daily fluctuation would represent in extreme cases a 18 to 22 mm. high water column, *i.e.*, a value of 18,000 to 22,000 g/m^2.

In order to quantitatively determine the daily changes in groundwater volume in a satisfactory manner, two further problems must yet be cleared. One of these is the fluctuation in the temperature of the voids alone caused by temperature changes determined for the entire soil mass [11, 17], and the variation in saturation vapour pressure therewith. The second problem remaining to be answered, is the determination of the pore volume affected by changes in the water volume due to daily fluctuations in the groundwater table.

Considering a steady lowering of the groundwater table, a daily reduction in groundwater volume corresponding to a 3 to 4 mm. high water column, *i.e.*, of 3000 to 4000 g/cm^2, could be established with certainty, which,

originating from greater depths, escapes from the soil during the daytime hours.

Neglecting changes in temperature with time the total moisture movement can, according to *Philip* and *de Vries* [11, 16] be described by the expression

$$\frac{\partial \theta}{\partial t} = -\nabla (q_m/\rho_l) = \nabla (D_\theta \nabla \theta_l) + \nabla (D_T \nabla T) + \frac{\partial K}{\partial z} \quad \ldots (2)$$

where

- θ = volumetric moisture content of the soil
- t = time
- q_m = moisture flux
- ρ_l = density of liquid water
- T = temperature
- K = $f(\theta)$ = unsaturated hydraulic conductivity
- D_θ = isothermal moisture diffusivity
- D_T = thermal moisture diffusivity
- z = vertical coordinate, positive upwards

Moisture movement can, accordingly, be resolved into three components, of which the first, second and third correspond to the moisture gradient the temperature gradient and gravity, respectively.

Let us consider now the types of moisture movement prevailing at different depths in the soil on a day in summer. The vertical distribution of soil temperature, as well as of saturation vapour pressure at different times on a warm day (8th July, 1957) are show in *Fig. 4.* Daily fluctuations in soil temperature extend down to a depth of 100 cm. Below this level the temperature is stable and decreases with depth. Corresponding to the temperature gradient, a downward moisture movement my occur

$$q_z = -D_T \nabla T \quad \ldots (3)$$

The moisture content decreases downward and upward moisture movement is initiated by the capillary potential

$$q = -D \nabla \theta_l \quad \ldots (4)$$

Water quantities conveyed by both movements are very small, having an order of magnitude of about

$$10^{-2} \text{ to } 10^{-4} \text{ g cm}^{-2} \text{ day}^{-1}$$

and the assumption, that the two opposite trends of movement create balanced conditions, lies close at hand. Owing to the low moisture content, gravitational water movement is impossible at smaller depths, and, since due to lack of rainfall the moisture received no supply for several days, that occuring in lower, more humid layers can only be insignificant.

In these cases, the most significant moisture movement is the flow of vapour due to changes in temperature, which was described by *de Vries* by the following expression [16]:

$$\frac{\partial \theta_v}{\partial t} = \frac{(n-\theta_l) h \beta}{\rho_l} \frac{\partial T}{\partial t} \quad \ldots (5)$$

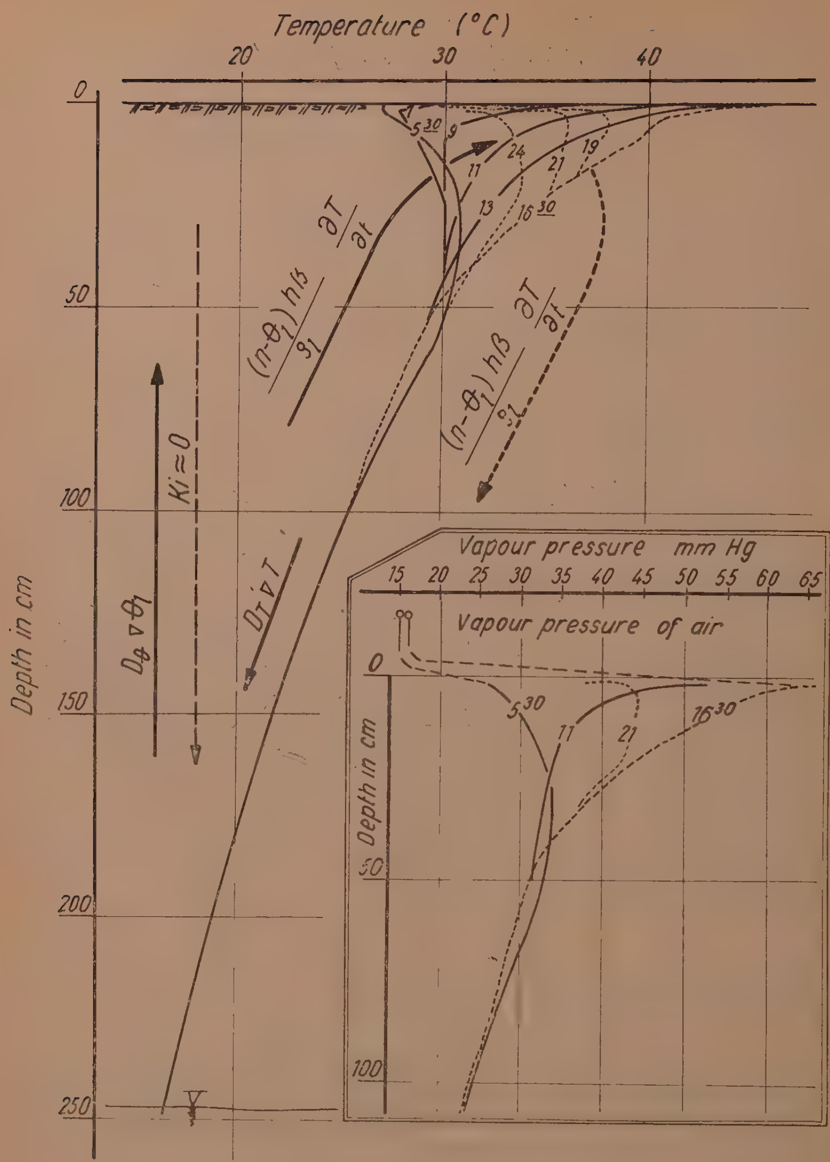

Fig. 4 Vertical distribution of soil temperature and saturation vapour pressure (mm mercury).

Numbers beside the curves denote the time of observation (hours). The distributions corresponding to dropping and rising groundwater tables are denoted by dashed and dotted lines respectively.

wherein:

θ_v = the volumetric vapour content
θ_l = the volumetric liquid content
n = the total pore volume of the soil (porosity)
h = the relative humidity, and
β = $d\rho_0/dT$ (ρ_0 is the saturation vapour content)

The above relationship is not suited for quantitative investigations. As revealed, however, by our observations, this type of moisture movement is highly significant.

An example for the case, where no fluctuation of the groundwater table occured due to the cooling of the upper layers, is shown in *Fig. 5*. The trend of soil-temperature changes observed at various depths has been entered on the upper part (a.) of the figure, changes in the groundwater table are indicated in the center part (b.), while the difference between temperatures at 2 and 50 cm. depths ($T_{2\,cm} - T_{50\,cm}$) are given in the lower part (c.). No fluctuation of the groundwater table occured at all on the 12th July 1957, since the upper layers cooled down to a temperature lower than that at greater depths and the daily variation of the air temperature was similarly low.

Resuming our observations concerning vapour movements in the soil due to changes in temperature the following statements can be made:

On warm days, when the temperature variation in the upper soil layers is great, significant movement of vapour occurs in the soil. During the day-time hours this results in a reduction of the moisture content and of the groundwater because of evaporation, whereas the water volume is increased by condensations during the night.

Evaporation from the soil depends upon the flow of vapour through the full thickness of the cover above the groundwater table. In case of artificially separated soil prisms both evaporation, and, as a result of different moisture distribution, infiltration may appreciably depart from those in case of natural soils. On the strength of these considerations we feel justified in contending, that natural water balance conditions of the soil cannot be approximated by weighable lysimeters, unless the latter extend down to below the groundwater table, which should be at the same depth within the lysimeter as in the natural soil. Shallow lysimeters containing no groundwater are unable to follow the trend of natural groundwaterbalance.

Data yielded on infiltration by non — weighable funnel lysimeters are but relative in character, and their departure from actual conditions is different in various parts of the year depending upon the natural heat—and waterhousehold of the soil. In case of funnel lysimeters an apparent increase in the water volume is caused also by lateral vapour inflow and by the condensation of vapour above the funnel. This phenomenon can be observed especially in case of funnel lysimeters having no upper edge of appreciable height [1, 6]. At the experimental station an apparent increase in water volume could be observed by three funnel lysimeters of 1 sq.m. area for every day on which appreciable daily fluctuation in the groundwater table occured. The quantity of water thus intercepted cannot be regarded as an increase in the water volume, since it did not enter from an outside source into the soil. During the daytime hours the vapour content of the soil pores increases by drawing upon the water stored in the lower layers. The funnels isolate the lower layers, but in want of a separating edge vapour enters to above the funnels laterally and condenses during the night.

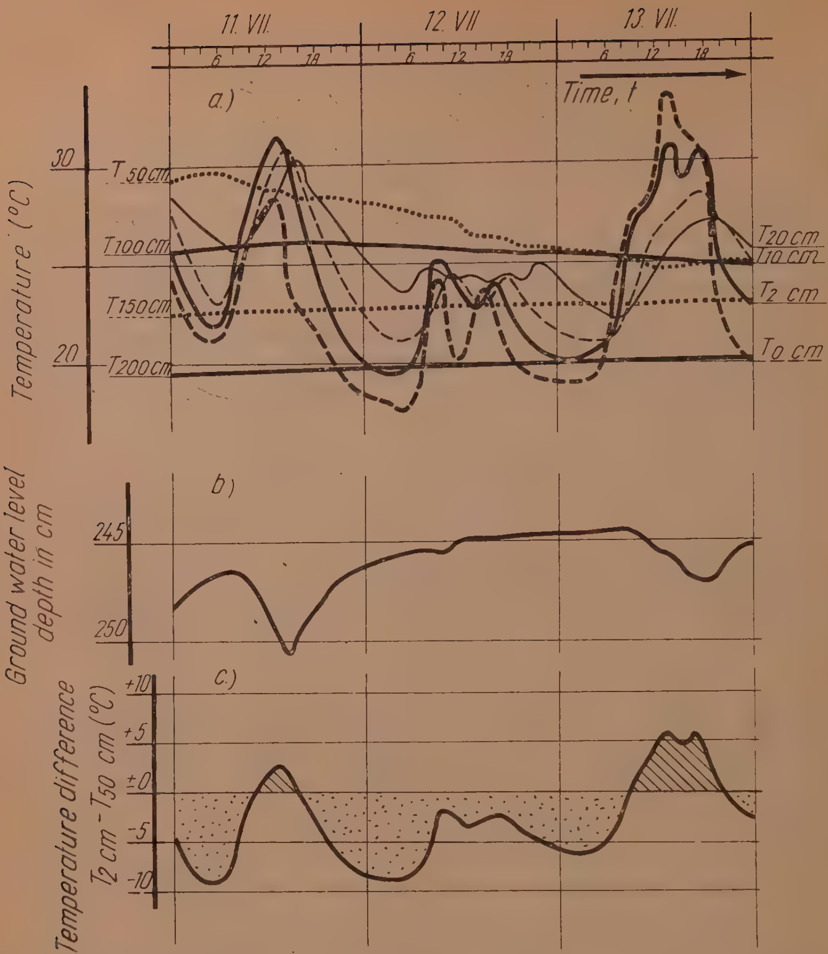

Fig. 5 No daily groundwater fluctuation occurs if the upper soil layers remain cool.
a.) Variation of soil temperature at various depths
b.) groundwater fluctuations
c.) temperature differential between 2 cm and 50 cm depths ($T_{2\,cm} - T_{50\,cm}$).

The moisture content of the atmosphere may also feed the water volume in the soil by condensation [3, 15]. Great care should be exercised in determining this water quantity. Condensation water, that was originally in the soil and changed over the vapour phase when the soil became warmer should carefully be distinguished from any increase in the water volume originating from outside.

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ÜBERBLICK ÜBER DEN STAND DER LYSIMETERMESSUNGEN IN DEUTSCHLAND

J. PRENK, MÜNSTER IN WESTF.

Unter Lysimetern werden Behälter verstanden, die den zu untersuchenden Boden enthalten und die dem Zwecke dienen, die Wasserbilanz dieses Bodens zahlenmäßig festzustellen. Die ursprüngliche Aufgabe der Lysimeter war vorwiegend agronomischer Art. Man bediente sich der Lysimeter, um mit ihnen die Nährstoffauswaschung der Böden zu studieren. Diese Lysimeter erhielten die verschiedensten Formen und Größen. Sie wurden aus Beton, Mauerwerk oder Eisen hergestellt und quadratisch oder zylindrisch ausgebildet. Durch eine im Boden des Behälters angebrachte Öffnung wird das Sickerwasser in Auffanggefäße abgeführt. Der Versuchsboden wurde entweder locker in die Lysimeter eingebracht oder auch eingestampft unter Angleichung an die gegebenen Profilverhältnisse.

Zu den ältesten Lysimetern dieser Art zählen die Lysimeter von v. Seelhorst (1) in Göttingen und Gerlach (2) in Bromberg. Ähnliche Anlagen wurden an den landwirtschaftlichen Instituten in Darmstadt und Weihenstephan eingerichtet. Die größte Anlage befindet sich auf der landwirtschaftlichen Versuchsstation Limburgerhof, die Eigentum der Badischen Anilin und Soda Fabrik AG Ludwigshafen ist (3).

All diese Anlagen, die in der Hauptsache dem Studium der Nährstoffbeziehungen zwischen Pflanze, Boden und Düngung dienten, brachten wertvolle Einblicke in die Sickerwasser- und Auswaschungsverhältnisse. Andererseits war man sich auch darüber klar, daß die so gewonnenen Ergebnisse nicht ohne weiteres auf natürliche Verhältnisse übertragen werden dürfen. Bei den sogenannten leichteren Böden mag das noch hingehen. Aber bei den schwereren Böden liegen die Dinge schon anders. Hier werden beim Verfüllen der Lysimeterkästen entweder hemmende, verdichtete Horizonte beseitigt, und dadurch der Wasserabfluß gefördert oder es wird die natürliche Dränung eines gut entwickelten Bodentyps unter Umständen restlos zerstört und es kann Jahrzehnte dauern, bis sich in einem solchen Lysimeter natürliche Bodenverhältnisse einstellen.

Der in aller Welt steigende Wasserbedarf auf der einen Seite, der begrenzte Wasservorrat auf der anderen, führt auch bei uns in Deutschland zwangsläufig zur planmäßigen Bewirtschaftung des Wassers. Diese planmäßige Bewirtschaftung setzt eine wasserwirtschaftliche Rahmenplanung und diese wiederum die Kenntnis der Wasserreserven insbesondere die der Grundwasserreserven voraus.

Die Erfassung der Grundwasserreserven ist nun nicht ganz einfach. Wasserwirtschaftler wie G. Schroeder, Wundt und Natermann haben dafür statistische Verfahren entwickelt, die es gestatten, aus den Abflußganglinien der natürlichen Wasserläufe das Maß der Grundwasserspeisung zu ermitteln (4). Diese Verfahren sind jedoch nicht in jedem Falle anwendbar. Ein typisches Beispiel dafür ist das rund 700 km² große Gebiet der Halterner Sande, das im Niederschlagsgebiet der Lippe, einem Nebenfluß des Rheins, im Land Nordrhein-Westfalen liegt. Diese Halterner Sande haben zum großen Teil überhaupt keinen Oberflächenabfluß und dort, wo offene Wasserläufe vorhanden sind, decken sich deren Niederschlagsgebiete keineswegs mit den Einzugsgebieten. Da hier seit einigen Jahren Grundwasserbeobachtungsbrunnen

stehen, hat man versucht, über die Grundwasserschwankungen die jährliche Grundwasserspeisung mengenmäßig zu erfassen. Mit diesem Verfahren kommt man aber erst recht nicht zum Ziel, da die Grundwasserspeisung sich aus einem Doppelintegral zusammensetzt, von dem sich nur eines auflösen läßt, nämlich das aus den vertikalen Grundwasserstandsänderungen.

Jedermann bei uns weiß, daß die Halterner Sande zu den größten Grundwasservorkommen Deutschlands zählen. Ihr Speicherraum ist von Geologen zu 18 Milliarden m³ errechnet worden. Doch das hat nicht viel zu besagen; denn entscheidend ist ja die jährliche natürliche Grundwasserspeisung aus den Niederschlägen und gerade sie ist bis jetzt noch so gut wie unbekannt und wie schon gesagt, mit den bisher bekanntgewordenen Verfahren nicht zu erfassen. So blieb uns nichts anderes übrig, als hier Versickerungsmeßstellen einzurichten, und wir hoffen und rechnen nunmehr, daß wir mit den dort bereits aufgestellten und noch aufzustellenden Lysimetern in nicht allzulanger Ferne zu brauchbaren Ergebnissen gelangen. Damit komme ich auf die Verwendung der Lysimeter für wasserwirtschaftliche und hydrologische Untersuchungen zu sprechen.

Die erste Lysimeteranlage, die nach hydrologischen Gesichtspunkten betrieben wird, wurde 1929 in Eberswalde bei Berlin von W. Friedrich u. J. Bartels eingerichtet (5). Seitdem sind in Deutschland in der Folgezeit Lysimeter für wasserwirtschaftliche Zwecke in steigendem Maße eingerichtet worden. Größere Anlagen befinden sich heute in Gießen, Dortmund (4), Karlsruhe (6), Sindorf bei Köln (7), Uedem am Rhein, in der Senne bei Brackwede, Hamm-Bossendorf und Lavesum bei Haltern, Garzweiler und als neueste, die Anlage in Berlin-Dahlem (8), um nur die bedeutendsten zu nennen. Von diesen werden Ihnen gelegentlich der Exkursion die Anlagen in der Senne, die bei Haltern und die Dortmunder Anlage gezeigt werden.

Diese nun nach hydrologischen Gesichtspunkten arbeitenden Lysimeter haben nicht nur den Vorteil, daß sie Ergebnisse auch dann bringen, wenn die herkömmlichen Verfahren versagen, sie gestatten darüber hinaus vielen anderen Fragen nachzuspüren, so vor allem der nach dem Einfluß der Faktoren, die das Maß der Grundwasserspeisung weitgehend mitbestimmen, also neben dem Faktor Boden die Faktoren Witterung und Bewuchs. Eine sehr angeregte Diskussion unter den Wasserwirtschaftlern bei uns hat z. B. die Frage ausgelöst, ob die laufende Steigerung der landwirtschaftlichen Erträge mit einer Minderung der Grundwasserspeisung verbunden sei. Diese Frage ist letztlich nicht anders als über geeignete Lysimeter zu klären. Wir haben zwar versucht mit einem Indizienbeweis den Nachweis zu führen, daß diese Art Minderung der Grundwasserspeisung nicht ins Gewicht fallen kann, aber überzeugt haben wir die Fachwelt davon wohl noch nicht ganz (9). Zur Klärung dieses Fragenkomplexes dient eine nach Angaben von Friedrich gebaute Anlage auf dem Versuchsfeld des Instituts für Pflanzenbau in Bonn und eine neue große Anlage in Berlin-Dahlem.

Entsprechend ihrem Verwendungszweck wurden die neueren Lysimeter w ä g b a r und n i c h t w ä g b a r ausgebildet. Die w ä g b a r e n bieten den Vorteil, daß für jeden beliebigen Zeitabschnitt alle Faktoren des Wasserhaushalts festgestellt werden können. Diesem Vorteil steht als Nachteil gegenüber, daß diese Anlagen einen größeren Aufwand für Einrichtung und Betrieb erfordern. Sie werden daher nur in beschränkter Zahl errichtet oder in Verbindung mit nicht wägbaren. Ausschließlich wägbare Lysimeter mit ortsfester Wiegevorrichtung stehen bei uns in Eberswalde, Karlsruhe, Uedem und im Berlin-Dahlem und eine solche mit fahrbarer Waage bei Dortmund.

Geht es nur darum, die Grundwasserleistung eines bestimmten Gebietes der Größe nach zu erfassen oder will man die Verdunstung eines längeren Zeitabschnittes bestimmen, dann reichen Anlagen mit *nicht wägbaren* Lysimetern vollkommen aus (10). Diese Anlagen erfordern im allgemeinen keinen großen Aufwand und bieten somit den Vorteil, daß sie in größerer Zahl errichtet werden können. Ein solches Objekt haben wir in den schon eingangs erwähnten Halterner Sanden, wo keineswegs nicht nur sandige Böden zu finden sind. Die Bodenartenskala reicht auch hier hinauf bis zum undurchlässigen Ton.

Es wurde schon vermerkt, daß bei den alten Anlagen die Versuchsböden in die Lysimeter eingefüllt wurden. Davon ist man aus bereits dargelegten Gründen weitgehend abgekommen. Es sind von Schroeder und Friedrich Verfahren entwickelt worden, die es ermöglichen, den Versuchserdboden in seiner natürlichen Lagerung in die Lysimeter einzubringen. Daneben sind Versuchsreihen angesetzt worden, um Lysimeter mit eingeschüttetem Boden unter sonst gleichen Bedingungen mit Lysimetern mit natürlich gelagertem Boden in ihrer Wirkungsweise zu vergleichen, so in Sindorf, Dortmund und Gießen.

Eines der neuen Verfahren, das zu untersuchende Bodenprofil ungestört zu erhalten, besteht darin, daß von einem Graben oder Stollen aus ein mit Filterkies angefüllter Trichter unter den natürlichen Erdkörper gedrückt wird. Diese Methode führte nicht immer zum Ziel, weil sich in dem Trichter über dem Filtermaterial hängendes Wasser bildete, das kapillar über den meist niedrigen Rand des Trichters gehoben und nach den Seiten abgeleitet wurde. Diesem Übel wurde später dadurch begegnet, daß dem Trichter ein etwa 80 cm hoher Kragen von unten her aufgeschoben wurde; allerdings ist noch nicht ganz geklärt, ob dieser 80 cm hohe Kragen auch in jedem Fall ausreicht. Den Messungen mit Trichterlysimetern haftet aber auch noch der Nachteil an, daß der Versuchskörper, dessen Wasserhaushalt ermittelt werden soll, keine seitliche Abgrenzung hat, und daß durch tierische Gänge und eingeschaltete schwer durchlässige Schichten das Wasser auf seinem Wege abwärts in unkontrollierbarer Weise abweichen kann.

Bessere Ergebnisse bringen Lysimeter, die nach folgendem Prinzip eingerichtet werden. Ein zylinderförmiger Lysimeterkörper von 1,13 m l. W. = 1 m^2 Auffangfläche wird durch Belastung unter gleichzeitigem Freigraben des Außenmantels bis zur erforderlichen Tiefe in den Versuchsboden gedrückt. Nach Schaffung einer hinreichend großen Baugrube wird mit Hilfe von Wagenwinden eine an der Stirnseite angeschärfte Bodenplatte eingeschoben, die den unteren Abschluß des Lysimeterkörpers bildet. Den Bauvorgang werde ich an Hand von einigen Bildern noch näher erläutern.

Bei der Ausführung nach diesem Prinzip mit geneigtem Boden wird die Bodenplatte mit dem Lysimeterkörper verschraubt und wasserundurchlässig abgedichtet oder verschweißt. Das Sickerwasser kann hier nur durch eine verhältnismäßig kleine Öffnung austreten. Nach dieser Methode sind 20 Lysimeter von Schroeder und Friedrich in Zusammenarbeit mit Tüxen in verschiedenen Böden errichtet worden, um den Zusammenhang zwischen Pflanzensoziologie und Wasserhaushalt zu klären. Bei waagerecht angeordneter Platte wird der Austritt des Sickerwassers allerdings dadurch erleichtert, daß der Lysimeterkörper noch auf eine mit Kies gefüllte Filterwanne gesetzt wird.

Was nun die Größen der Lysimeter anbelangt, so ist dazu zu sagen, daß die Güte der Beobachtungsergebnisse davon abhängt, wieweit sich der im

Lysimeter eingeschlossene Versuchskörper in bezug auf den Wasserhaushalt so verhält wie der natürliche Erdboden. Die Tiefe muß eine ungehinderte Wurzelentwicklung zulassen und die verdunstende Oberfläche muß so groß sein, daß der Pflanzenwuchs nicht gehemmt wird, und daß die Randeffekte möglichst vernachlässigt werden können. Lysimeter von 1 m^2 Auffangfläche und etwa 2 m Tiefe dürften allgemein diesen Forderungen genügen. Lysimeter, die in landwirtschaftlich genutzten Flächen und mit der Oberkante etwa 30 cm unter Flur stehen, müßten dabei die besten Ergebnisse bringen, einmal weil die sonst unvermeidlichen Randeffekte hier im Gegensatz vor allem zu den wägbaren Lysimetern so gut wie gar nicht auftreten können, zum andern deshalb, weil die Flächen dieser Lysimeter der gleichen Bewirtschaftung unterliegen, wie die Felder, in denen sie stehen.

Ein besonders schwieriges Problem ist der Wasserhaushalt des Waldes. Seiner Erforschung sollte vor allem die Anlage in Eberswalde dienen. Es liegen darüber auch schon einige Veröffentlichungen von Friedrich vor (11). Inzwischen ist eine ganz neue Anlage in den Halterner Sanden entstanden, und zwar unter Laub- und Nadelwald nicht weit entfernt von Lysimetern, die frei in landwirtschaftlich genutzten Flächen stehen. Einzelheiten sind aus den nachfolgenden Abbildungen zu ersehen:

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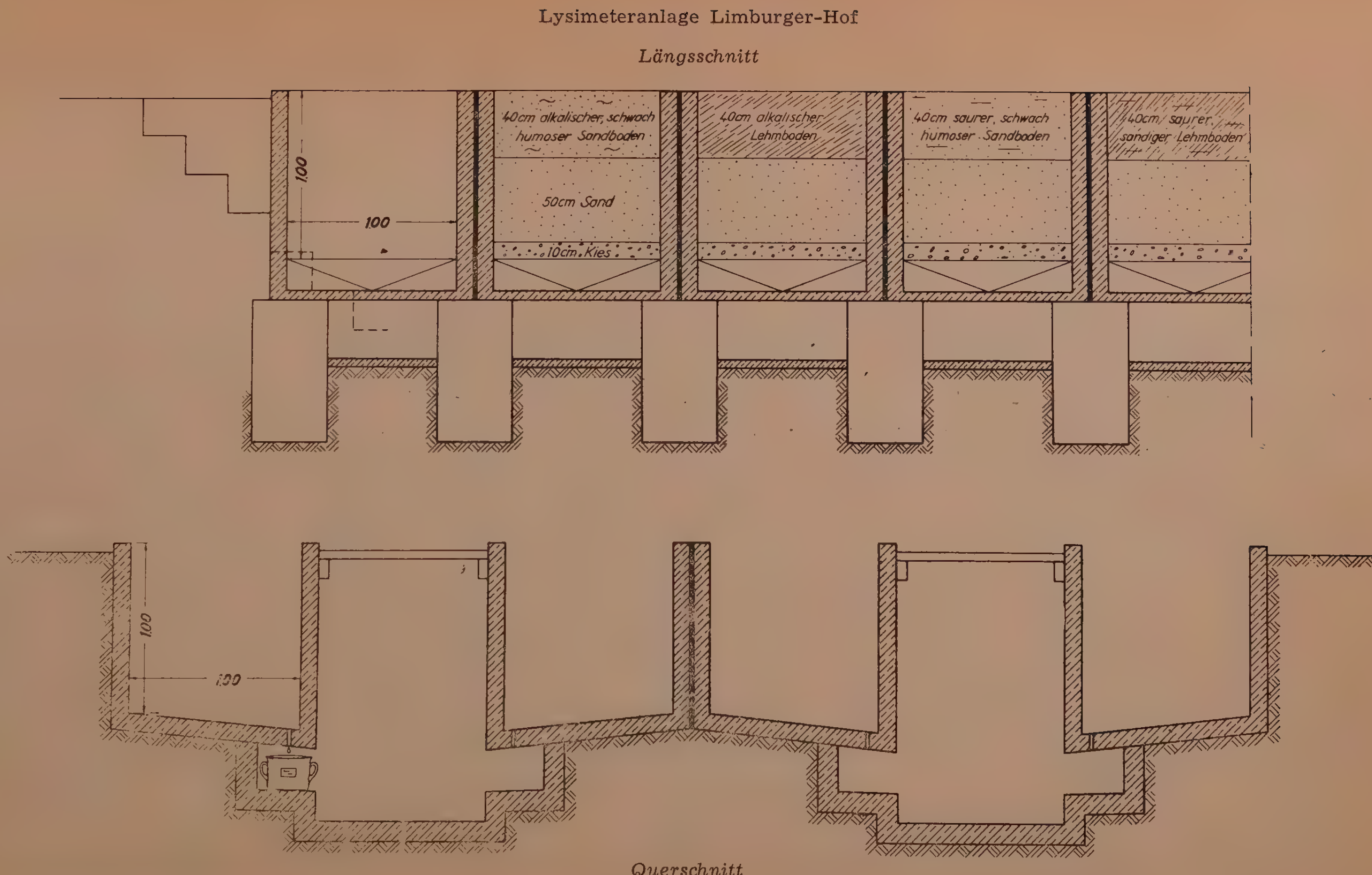


Fig. 1 Lysimeter-Anlage Limburger-Hof. 232 Behälter, nicht wägbar, eingefüllter Boden. Nutztiefe 1,00 m um 1930 entstanden.

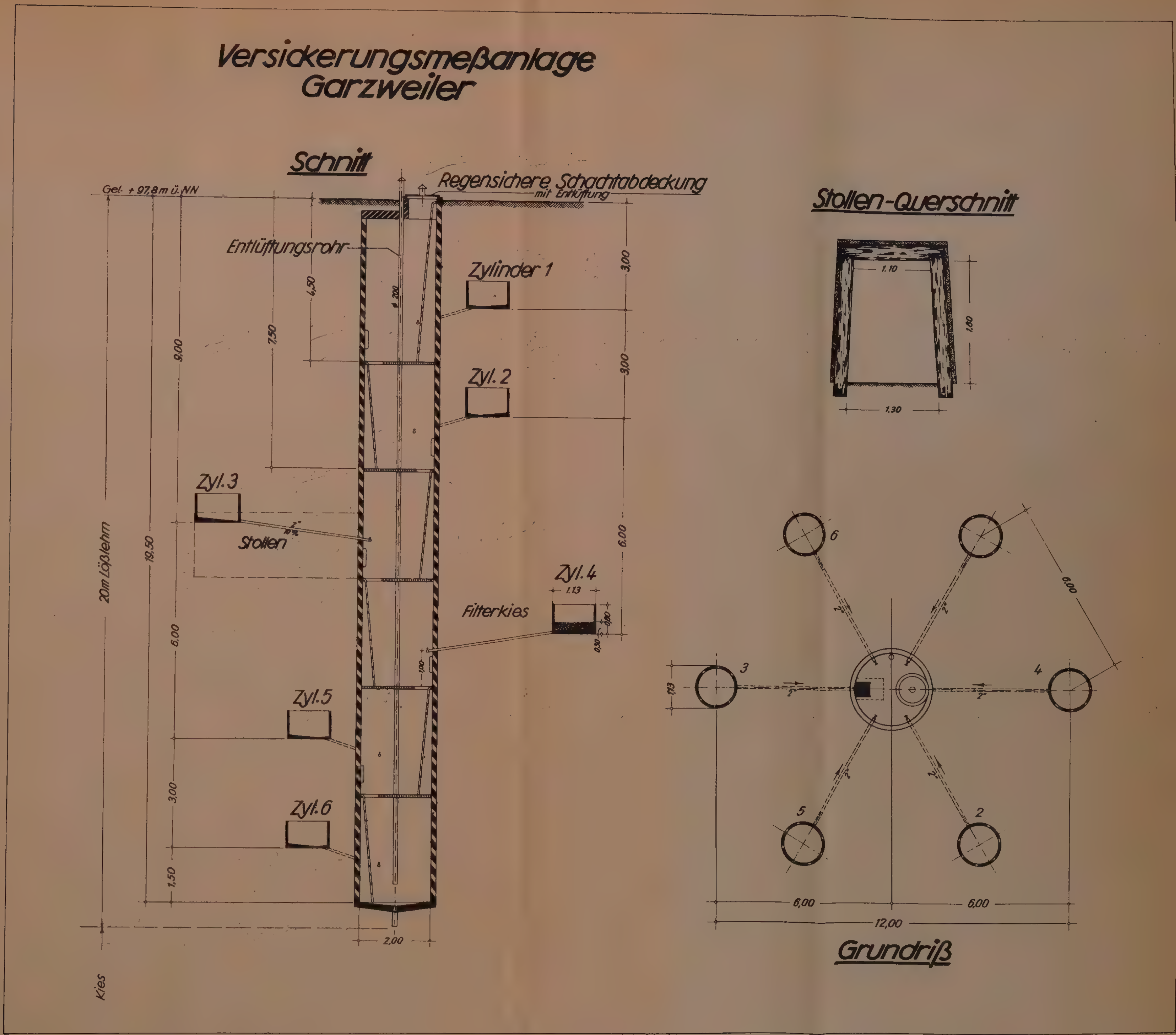


Fig. 2 Lysimeter-Anlage Garzweiler. Nicht wägbar; Trichterlysimeter mit 80 cm hohem Kragen und Kiespolster in verschiedenen Tiefen in den gewachsenen Boden einer 17 m mächtigen Löß-Auflage gepreßt; natürlicher Bewuchs. 1957 fertiggestellt.

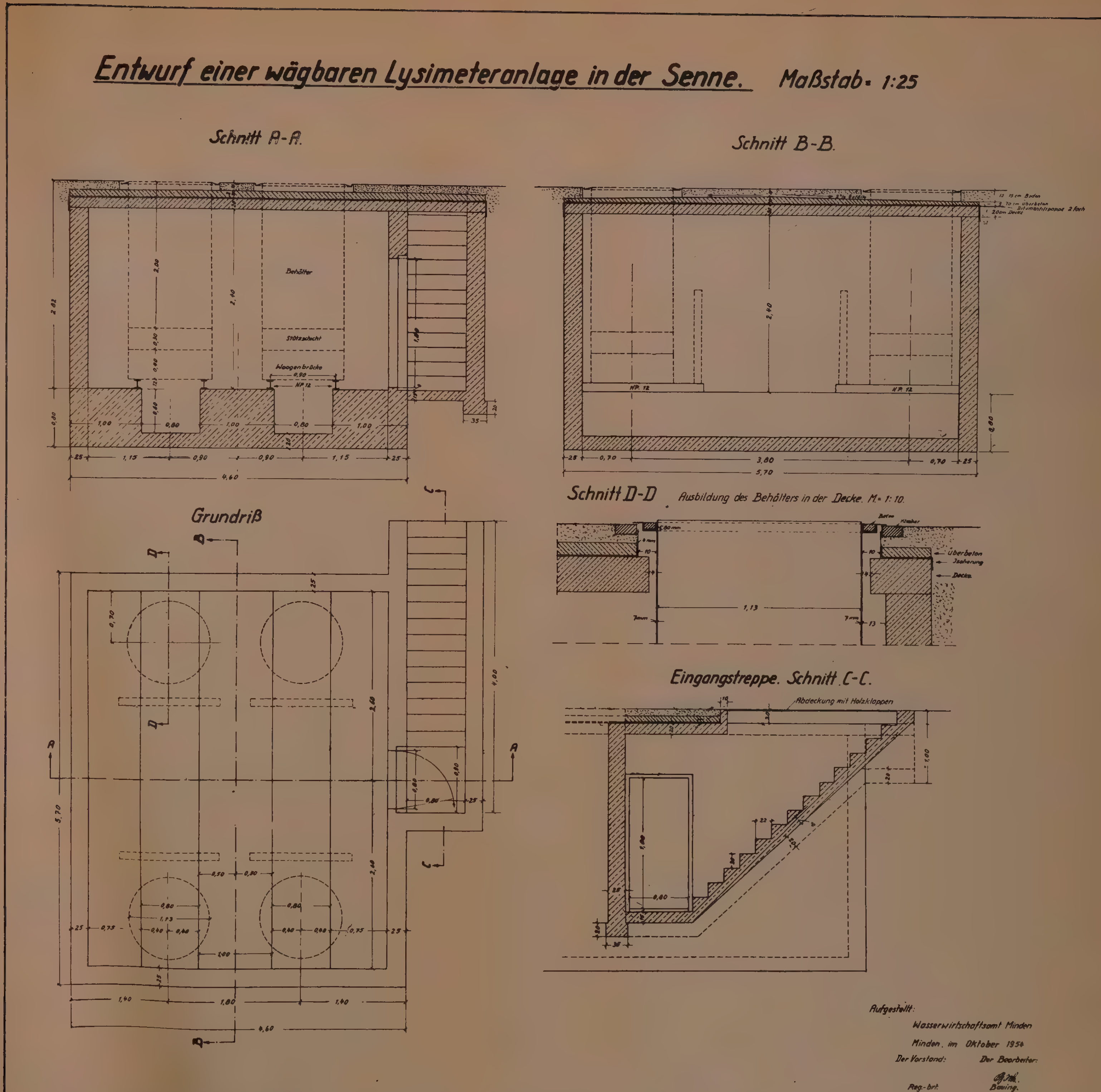


Fig. 3 Lysimeter-Anlage Senne. 4 wägbare Lysimeter, 1 Behälter mit Sennesand, 2 Behälter mit Lößlehm, 1 Behälter mit Wealdenton, 1 Behälter eingefüllt, 3 Boden-Monolithe auf Kiespolster, Nutztiefe 2,00 m. 1955 fertiggestellt.

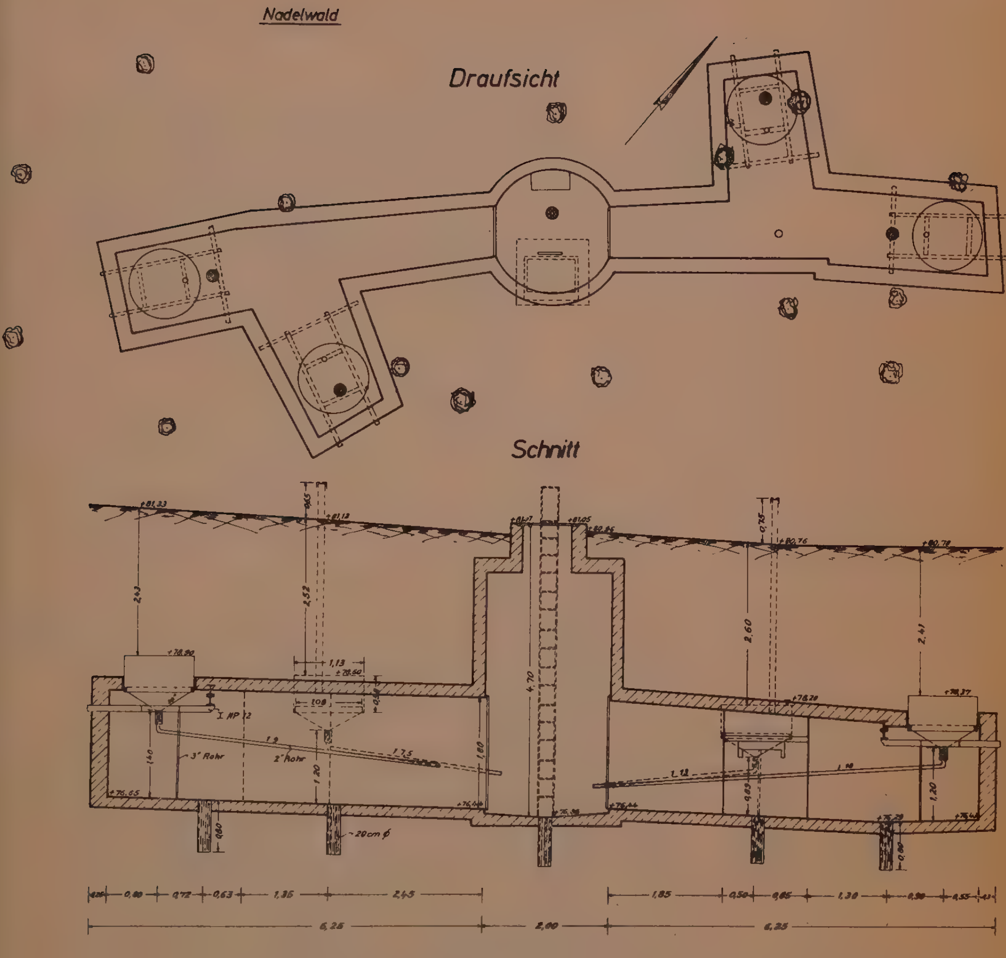


Abb. 4 Lysimeter-Anlage bei Haltern unter Nadel- und Laubwald. 4 Trichterlysimeter mit hohem Kragen und Kiespolster, nicht wägbar, natürlicher Bewuchs, 4 verschiedene Situationen. Nutztiefe 2,40 bis 2,60 m. 1957 fertiggestellt.

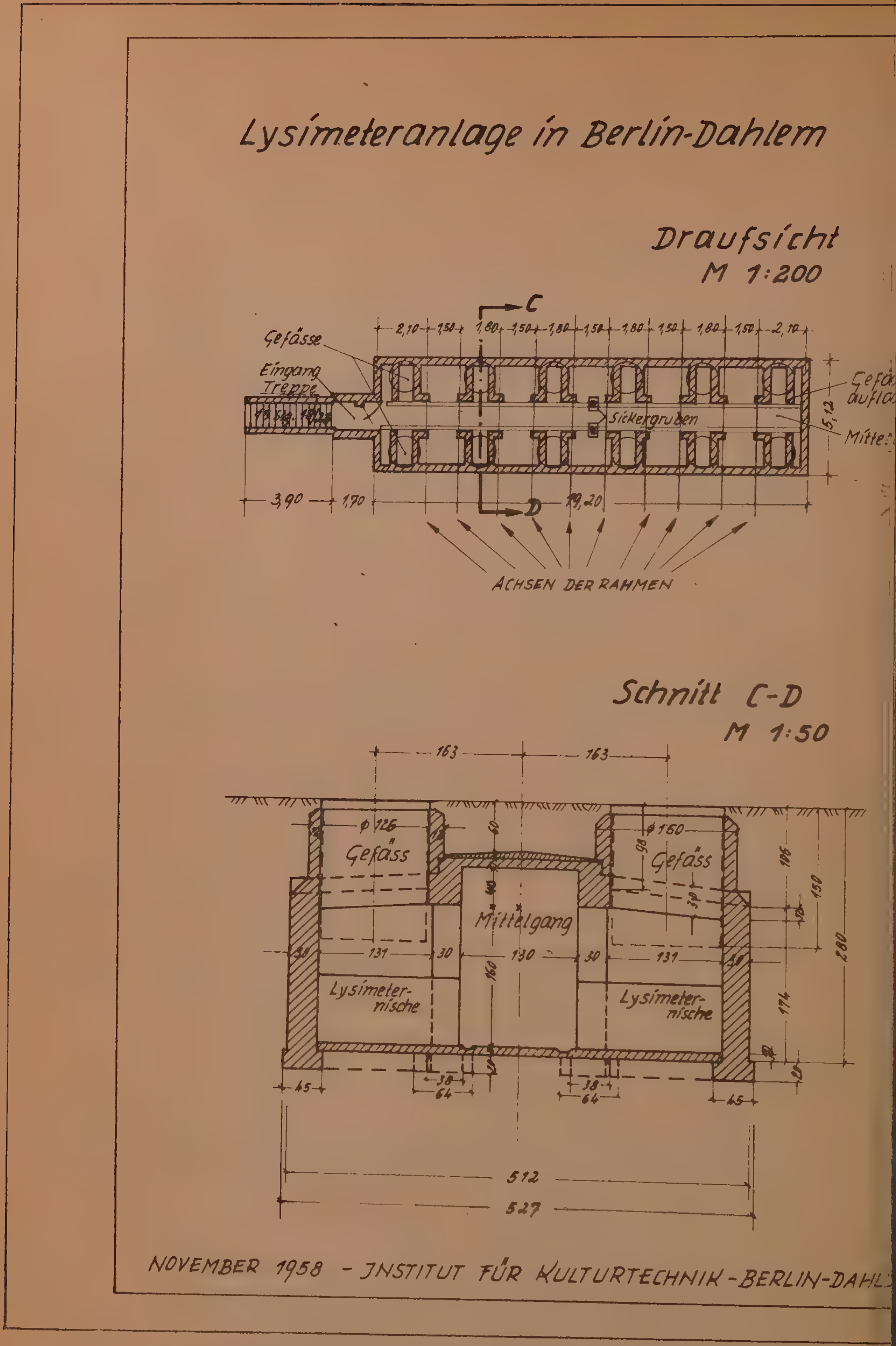
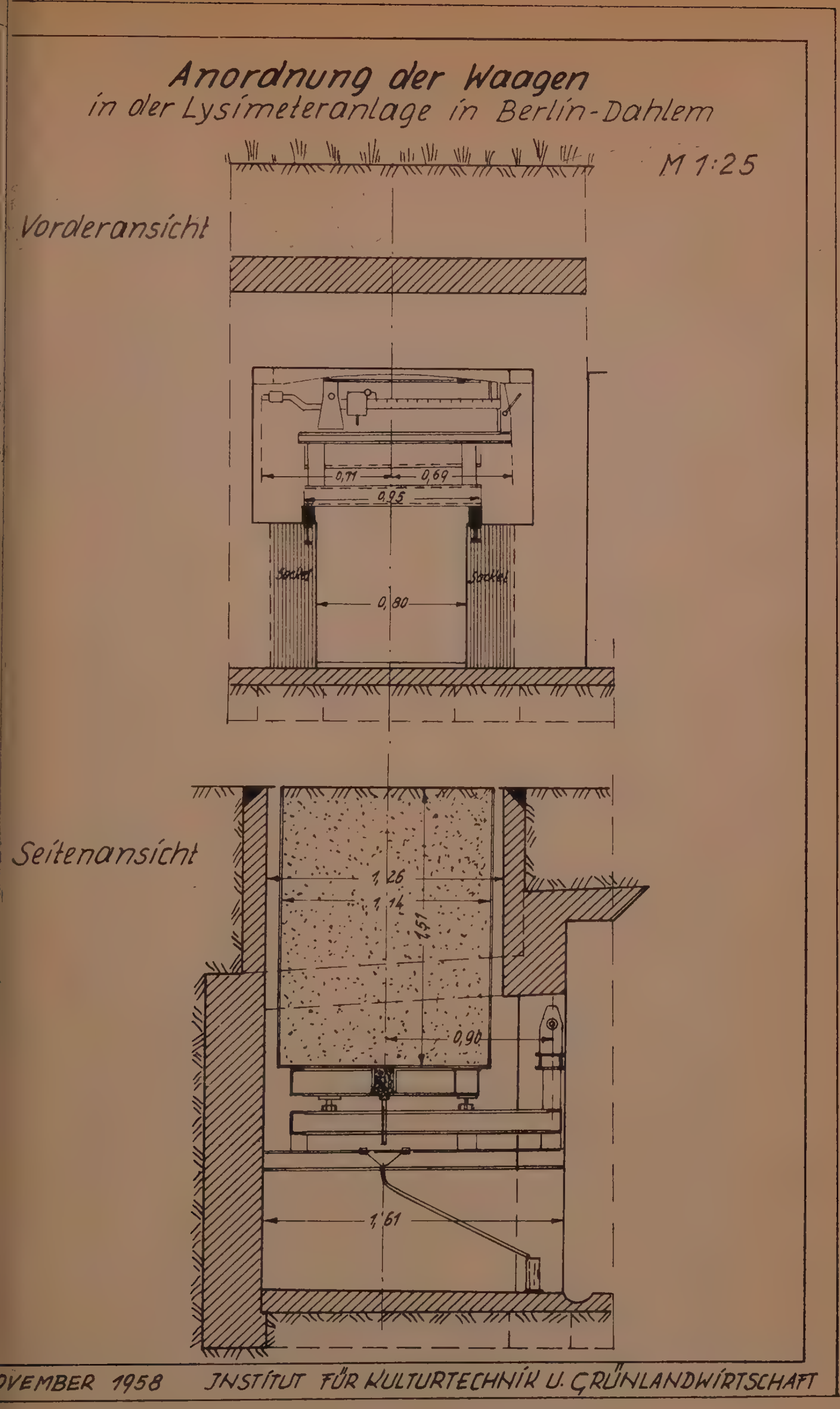


Fig. 5 Lysimeter-Anlage Berlin-Dahlem. 8 wägbare, 4 nicht wägbare Behälter, Bodenmonolithe, 1,50 m Nutztiefe, Anlage dient der Untersuchung des Wasserhaushaltes bei verschiedenen Nutzungen (ungenutzt, extensiv u. intensiv) und der Untersuchung des Sickerwassers auf Stoff- und Keimgehalt mit Reinwasser und vorbehaltenem Abwasser. Fertiggestellt 1958/59.


Anordnung der Waagen
in der Lysimeteranlage in Berlin-Dahlem
M 1:25
Vorderansicht
0,71
0,69
0,95
Sockel
Sockel
0,80
Seitenansicht
1,26
1,14
1,51
0,90
1,61
NOVEMBER 1958
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